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Implications of Advanced Technologies for Air and Spacecraft Escape

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.472

IMPLICATIONS OF ADVANCED TECHNOLOGIES FOR AIR AND SPACECRAFT ESCAPE

Papers presented at the Aerospace Medical Panel Symposium held in Munich, Germany, from 24 to 28 April 1989.

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PREFACE

In spite of continuing improvements in safety, performance envelope and reliability of present operational aircraft escape systems, further upgrading is desirable particularly with respect to high airspeed, adverse attitude and low altitude recovery. Reduction of escape fatalities or injuries and out-of-the envelope ejections are the primary goals. Escape from hypersonic vehicles and spacecraft are additional challenges of the future. Advanced technologies impact escape systems in two ways: increased aircraft (and space systems) performance expands the requirements envelope and advanced technologies in aerodynamics, materials, control, propulsion, avionics, sensors and crew protection enable the design of intelligent escape systems with automatic hazard assessment and adaptation to the specific situational need.

This Symposium assesses technological advances in all areas which affect overall escape system performance and capabilities. The multi-disciplinary discussions is centered on new studies, development efforts, human tolerance and system design criteria, and tests that highlight advances in overall system capabilities and future opportunities.

• • •

PREFACE

Malgré les améliorations qui sont apportées à la sécurité, à la fiabilité et aux performances des systèmes d'évacuation des aéronefs, des perfectionnements sont toujours à souhaiter en ce qui concerne le vol à grande vitesse, les positions inhabituelles et la récupération à basse altitude. Toutes ces améliorations ont pour objectif principal de réduire le nombre d'accidents mortels ou blessures survenant suite à l'évacuation de l'aéronef, ainsi que le nombre d'éjections hors enveloppe de vol. L'évacuation des véhicules hypersoniques et spatiaux est un défi pour l'avenir. L'impact des technologies de pointe dans les systèmes d'évacuation se répercute de deux facons: d'une part l'accroissement des performances des aéronefs et des systèmes spatiaux augmente les spécifications dans l'enveloppe de vol, et d'autre part les technologies avancées dans les domaines de l'aérodynamique, des matériaux, du contrôle, de la propulsion, de l'avionique, des capteurs et de la protection du personnel navigant permettent la réalisation de systèmes d'évacuation intelligents avec prévision automatique de risque de d'adaptation aux besoins conjuncturels.

Ce Symposium fait le point des progrès réalisés dans tous les domaines ayant une influence sur le fonctionnement global et les capacités des systèmes d'évacuation. Le débat pluridisciplinaire porte sur les études nouvelles, les projects de développement, les niveaux de tolérance humains et les critères à adopter pour la conception des systèmes, ainsi que sur les essias destinés à mettre en valuer les nouvelles possibilités des systèmes et les applications futures.

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INTRODUCTION AUX IMPLICATIONS DES TECHNOLOGIES DE POINTE DANS L'EVACUATION DES AERONEFS ET DES VEHICULES SPATIAUX.

Prof. H. VIEILLEFOND

Médecin-Chef du Laboratoire de Médecine Aérospatiale
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L'abondon de bord des aéronefs en difficulté au cours du vol est un besoin apparu dès l'origine de l'aviation de combat. Au cours de la première guerre mondiale plusieurs pilotes durent payer de leur vie l'absence de moyen d'aide à l'évacuation de l'avion touché par l'ennemi. Entre les deux guerres, l'utilisation systématique du parachute a permis de résoudre une partie du problème jusqu'au jour où la vitesse des avions est venue rendre problématique la sortie du pilote et hasardeuse sa trajectoire dans les airs.

A partir d'une vitesse de l'ordre de 300 à 400 km/h le pilote ne peut quitter lui-même son avion en raison de la pression dynamique exercée par le vent relatif. De plus la collision du pilote avec l'empennage est très souvent responsable des nombreux accidents observés. Dès lors l'éjection par siège propulsé est le seul mode d'évacuation de la cabine.

C'est juste avant la seconde guerre qu'en Allemagne débutent les études d'une aide mécanique à l'abandon de bord. Elles devaiant conduire rapidement à l'utilisation opérationnelle des premiers sièges éjectables et à la fin de la guerre il y avait eu 60 éjections dans la Luftwaffe. Depuis le nombre d'éjections enregistrées dans le monde dépasse très largement 10.000.

Mais aujourd'hui, au cours des missions de pénétration tactiques ou stratégiques, il est devenu particulièrement important de voler le plus vite possible à très basse altitude, de façon à échapper aux radars et aux tirs des missiles anti-aériens adverses. Les missions d'attaque au sol nécessitent, elles aussi, le vol à très basse altitude et comportent de nombreuses manoeuvres d'évitement.

Ces types de vol constituent des conditions très défavorables à l'abandon de bord en vol. Si l'on se réfère au travail que James Brinkley a présenté lors de la réunion de notre Panel à Williamsburg en mai 1984, on peut considérer que 60 % des éjections fatales de l'USAF pendant la décennie 1973-84, ont été considérées, par les commissions d'enquête, comme réalisées hors du domaine du siège éjectable utilisé. Dès lors on peut considérer comme hors domaine, les éjections effectuées au dessous de 150 m et à des vitesses supérieures à 600 kts.

Pour imprimer au pilote assis sur son siège une trajectoire de sécurité évitant en particulier les structures arrières de l'avion, ou les pales du rotor principal des hélicoptères, il faut lui donner une vitesse d'autant plus grande que celle de l'avion est élevée et que les dimensions de l'empennage sont plus importantes. Le temps dont on dispose pour atteindre cette vitesse est si court que l'accélération est nécessairement très élevée, à la limite de la tolérance humaine.

Si l'on veut donner au siège des vitesses supérieures il faut augmenter la durée de l'accélération mais diminuer son intensité. C'est ce qui est réalisé avec les sièges à fusée autorisant une apogée de la trajectoire d'éjection assez haute pour permettre le déploiement du parachute même sans vitesse horizontale initiale de l'avion.

Malgré cela, dans près de 15 % des éjections réussies, la survie du pilote n'est obtenue qu'au prix de lésions parfois sévères du rachis, en particulier dorsal ou au niveau de la charnière dorsolombaire.

En fait nous n'avons pas encore de bon modèle de la résistance vertébrale à l'accélération. L'un des plus connus, utilisé par l'USAF est à un seul degré de liberté. De ce fait, l'index de réponse ou "dynamic response index" n'est applicable qu'au seul axe Gz et ne peut prendre en compte des positions du pilote sur son siège qui représentent pourtant un des facteurs pathogéniques les plus importants dans le mécanisme d'apparition des fractures du rachis. La recherche d'un angle aussi petit que possible entre l'axe du rachis et celui de la poussée du canon devra être une de nos préoccupations.

On considère en général que la configuration normale de l'éjection implique le vol rectiligne de l'avion sur une trajectoire sensiblement horizontale et sous facteur de charge unitaire, le pilote étant correctement assis et sanglé sur le siège. Il est pourtant clair qu'au cours des missions de guerre et tout spécialement au cours du combat tournoyant, l'éjection pourra avoir lieu en virage serré. L'accélération engendrée par la manoeuvre s'ajoute alors à l'accélération du siège. Dans les vrilles, l'accélération transverse développée par la rotation de l'avion placera le rachis en flexion forcée aggravant les risques de fracture.

Il ne sera sans doute pas facile de mettre au point des modèles prenant en compte tous ces facteurs et il sera peut-être encore plus difficile de les valider pour l'homme, ne serait-ce qu'à cause du risque encouru par les sujets volontaires. Nous verrons sans doute au cours de cette réunion ce que l'on peut attendre de la mise au point de nouveaux mannequins anthropomorphiques.

Une fois le siège mis à feu on est tenté de mettre au plus tôt le pilote sur sa trajectoire par exemple en supprimant la phase de largage de la verrière. Le pilote et son siège traversent alors la verrière préalablement fragilisée par des cartouches pyrotechniques. On peut escompter un gain de l'ordre de la seconde mais le risque de détérioration des équipements est plus grand. Le danger que représente une collision avec un morceau de plexiglass plus ou moins volumineux, pris dans le vent relatif, reste difficile à préciser.

Le principal danger qui guette le pilote à sa sortie de la cabine est représenté par la pression dynamique qu'exerce le vent relatif. Cette pression qui dépend de la densité de l'air varie aussi comme le carré de la vitesse. C'est dire son importance lors des éjections à basse altitude et grande vitesse.

Cette pression est responsable d'effets directs sur le corps et en particulier sur la face, tels que contusions, pétéchies, hémorragies sous-conjonctivales. La protection apportée par les équipements, visière de casque, masque n'est pas toujours suffisante et il n'est pas rare que ces équipements soient justement arrachés par le vent relatif avec tout ce que cela peut supposer de défavorable lors des éjections réalisées à haute altitude. Mais cette pression ou "force g" est parfois à l'origine de blessures extrêmement graves liées à de véritables dislocations sinon arrachements de la tête et des membres. Il a été démontré que pour des vitesses de l'ordre de 450 kts, la pression dynamique est de l'ordre de 30 kPa, et que, dans ce cas, la force de contraction musculaire n'est ni assez rapidement établie ni assez puissante pour s'opposer au déplacement d'un membre dans le vent relatif.

La protection du pilote contre ce danger devra absolument être prise en compte pour les avions futurs et spécialement dans les phases de combat où la vitesse d'éjection est statistiquement toujours plus grande qu'à l'entraînement. Elle pourra faire appel soit à des équipements portés en vol par le pilote, soit à des caractéristiques particulières des sièges mais nécessitera de toute façon de difficiles études de balistique réalisées sur modèle anthropomorphique en soufflerie et leur validation au cours d'expériences sur sujet humain poseront là encore des problèmes d'éthique.

Dès que l'ensemble siège-pilote se trouve dans le vent relatif celui-ci est soumis à des mouvements de rotations vers l'avant à basse vitesse ou vers l'arrière pour des vitesses plus grandes et auxquelles s'associent des rotations latérales droites ou gauches. Or ni la tolérance cardio-vasculaire et respiratoire ni la tolérance aux effets vestibulaires des rotations ne sont excellentes chez les sujets non entraînés. On tentera donc grâce à des parachutes stabilisateurs ou par la poussée de petites fusées d'appoint de maintenir autant que faire se pourra le pilote et son siège sur une trajectoire stabilisée.

En ce qui concerne l'abandon de bord des hélicoptères, le problème est tout aussi ardu et la plupart du temps, en vol, il n'existe qu'une alternative l'autorotation et l'évacuation. Encore celles-ci nécessitent-elles le contrôle de l'appareil, une altitude suffisante, des conditions atmosphériques favorables et notamment de visibilité, un terrain d'atterrissage convenable, etc... Cette procédure est de toute façon inadéquate pour les futurs hécoptères de combat. Pour ceux-ci il faudra mettre au point des procédés d'éjection selon une trajectoire en L qui pourrait éviter le rotor principal et ses pales.

Pour les hélicoptères multiplaces on parle depuis déjà longtemps de techniques qui permettraient de transformer le cargo en une cabine largable et récupérable après séparation des gros morceaux inutiles moteurs, queue, rotors.

C'est vers des technologies de ce type que l'on s'oriente pour tenter le sauvetage des équipages de véhicules spatiaux. Comme pour les hélicoptères, les moyens d'abandon de bord font cruellement défaut en astronautique. La tragédie de Challenger doit nous inciter à proposer des moyens d'évacuation de bord au moins pendant le tir et les premières secondes du vol comme pendant les derniers instants du retour.

Nous aurons probablement aujourd'hui un début de réponse à cette question.

Pour "Hermès" un projet très ambitieux est à l'étude. Il consiste à éjecter une cabine permettant le sauvetage des trois membres de l'équipage dans les 120 premières secondes après le tir, jusqu'à Mach = 7 et 58 km. Le coût estimé d'un tel système est de 120 millions $.

Nous allons bientôt parler de technologies de pointe mais, nous médecins, ne devons pourtant pas oublier que ces aéronefs, ou ces véhicules spatiaux sont servis par des hommes. Ceci sousentend en particulier que l'abandon de bord reste une décision du commandant de bord et que même très automatisée elle reste une procédure faisant appel à la participation volontaire d'un être conscient.

Le respect des consignes d'éjection est le fruit d'un entraînement dans les cabines d'aéronefs et dans les simulateurs au cours duquel des automatismes doivent être acquis. En effet la seule connaissance théorique, même parfaite des procédures d'éjection est insuffisante car en situation réelle. il faudra faire très vite. On sait que le stress peut ralentir le temps de réaction et peut même entraîner l'inaction complète.

La volonté du pilote de contrôler son avion jusqu'au bout, sa hantise d'être à l'origine d'une catastrophe pour des populations civiles sont aussi un facteur important du retard à la prise de décision d'abandon de bord.

Et maintenant, après ces quelques réflexions, je crois que nous pouvons nous mettre au travail.

DEVELOPMENT OF ACCELERATION EXPOSURE LIMITS FOR ADVANCED ESCAPE SYSTEMS

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SUMMARY

Transient and angular accelerations significantly affect aircrew safety during emergency escape from aerospace vehicles. However, due to the scarcity of laboratory data on the response of the human body to transient, multiaxial acceleration, criteria for design and evaluation of escape systems have been restricted to relatively simplistic limits of acceleration magnitude and rate of acceleration onset for acceleration vectors acting in three orthogonal axes, with the exception of the foot-to-head direction (+Z axis). Mathematical models have only been used to assess the probability of injury for acceleration acting in the +Z axis. Limits have not been specified for angular acceleration. The United States Air Force is currently engaged in an advanced development program to demonstrate the feasibility of three-dimensional thrust-vector control to provide ejection seat attitude control and trajectory steering. This program has served to stimulate the development of more comprehensive design and evaluation criteria to assure that the thrust-vector control system functions without causing an unacceptable risk of injury to the escape system occupant. A method was developed to limit acceleration exposure on the basis of the computed responses of three orthogonal dynamic models. The method was initially developed using existing data from tests with human subjects and experience with operational escape systems. More extensive research is now ongoing to evaluate and improve the method. Impact experiments with volunteers have been accomplished to more precisely define the properties of the dynamic response models. Escape system test data were analyzed, including measurements of linear acceleration and angular velocity. This paper describes the acceleration exposure limit method, summarizes the results of recent impact tests accomplished with volunteers and provides revised dynamic response model coefficients derived from the results of these tests. Recent applications of the acceleration exposure method include evaluation of the performance of the ACES II ejection seat, development of the CREST advanced escape system technologies demonstrator, and study of crew escape systems for hypersonic flight vehicles. Future research directions are also discussed.

INTRODUCTION

Specification of the limits of human tolerance to short-duration acceleration is an extremely difficult problem. First, experiments to cause injury of living humans are clearly an unacceptable approach to acquiring the data to define these limits. Tests of human cadavers allow the exploration of stress levels that will cause injury, but the results of these tests have frequently indicated the likelihood of injury at levels that are known to be well tolerated by volunteer subjects or individuals involved in accidents. Therefore, one must use the limited results of early experiments with human subjects where injury was inflicted accidentally due to ignorance of the actual risks, interpret sketchy information available from vehicular accidents, and develop a basic understanding of human body dynamics from tests conducted at non-injurious levels. Second, it is difficult to extrapolate from a set of conditions known to cause injury to another set of conditions whose effects are not directly known. In the infancy of escape system design and development, aeromedical research was focused on the development of criteria for ejection seat catapults (1,2). The primary issue that was addressed was: What set of acceleration conditions are well tolerated by the ejecting aviator but will also provide an adequate velocity so that the seat and its occupant will clear the tail of the aircraft? Although a rectangular acceleration waveform would provide the most efficient means of developing the greatest velocity within a given catapult stroke length, the investigators determined experimentally that the human body response was more violent when the time to the peak acceleration was very short. The acceptable acceleration condition was found to have the waveform shown in Figure 1 (3). For catapult design purposes, human tolerance limits could thus be easily described in terms of two parameters, peak acceleration level and rate of onset of the acceleration. This same approach was used to develop the human tolerance criteria for the aerodynamic deceleration phase of escape from high-speed aircraft and the development of the ejection catapult for downward ejection seats (4,5). The approach seemed to be adequate to deal with the acceleration conditions during the catapult phase of emergency escape and in the interpretation of the results of tests with volunteers conducted using a rocket-propelled sled. But the limit parameters were difficult to apply to acceleration measurements made during inflight or rocket-sled tests of ejection seats. The idealized acceleration profile that was presumed to use the two-parameter exposure limit method only occurs if the ejection seat is aerodynamically stable, i.e., its attitude remains fixed with respect to the wind vector throughout the deceleration phase of the escape sequence. Unfortunately, ejection seats are not aerodynamically stable.

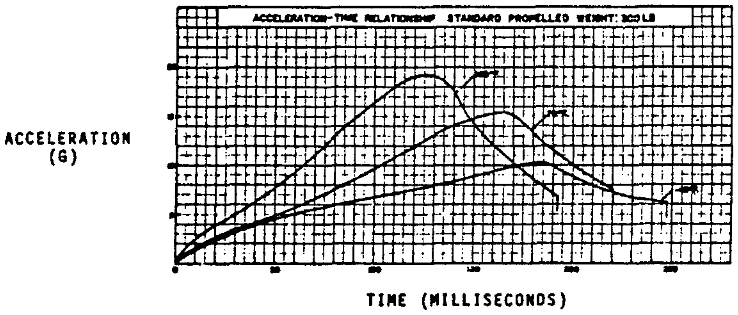


Figure 1. Acceleration-Time Profile of the M-5 Ejection Catapult (3)

Although investigators such as Stapp accomplished admirable and even heroic research to establish human acceleration limits, the complex multiaxial accelerations associated with more advanced escape systems such as the B-58 and B-70 encapsulated seats become practically impossible to evaluate using the peak acceleration and rate of onset criteria that were standardized (6). Although various committee-derived techniques were used, e.g., ignoring accelerations having durations under a specific duration, no consistent theoretically sound procedure was universally accepted. Kornhauser (7) first proposed a theoretically based technique and demonstrated the validity of one of its major premises by experimentation with small animals. Payne expanded the technique proposed by Kornhauser and mathematically demonstrated the power of the technique to analyze the effects of complex acceleration waveforms and to understand the basic principles of impact protection systems (8,9).

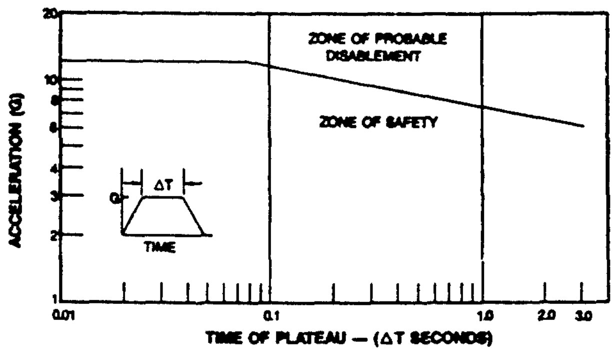
The approach proposed by Payne as well as others such as von Gierke (10), used mathematical models that are descriptive of mechanical system analogs of the dynamic-response characteristics of the human body. Although more complex models, such as those developed to explain human responses to vibration, were initially explored, simple single-degree-of-freedom, lumped-parameter models appeared to be adequate to explain the limited available test data applicable to escape systems.

The model that was developed to the most satisfactory degree was the Dynamic Response Index (DRI) model (11), which was developed to estimate the probability of compression fractures in the lower spine due to acceleration directed along the longitudinal axis of the spine in a pelvis-to-head direction (+Z axis). This model was verified by comparing the response of the model to ejection catapult accelerations with the operational injury rates associated with the specific escape systems (12,13). After operational verification and use of the model in the analysis of data from tests of several developmental escape systems, the DRI model was incorporated into the United States Air Force and multinational specifications for ejection seats and escape capsules (14,15,16). The DRI model was then successfully used in the design, test, and evaluation of the ACES II and the SIIIS-3 ejection seats.

Development of X-axis models proposed by Payne was impeded by the lack of sufficient data to verify the coefficients of the models or to approximate the likelihood of injury associated with the response of the model. Fortunately, additional experimentation with volunteers was continued to study the human response to short-duration acceleration. This work has included the investigation of human whole-body response (e.g., 17,18,19,20,17,18,19,20,21,22,23) and the response of specific body segments such as the neck and head (e.g., 24,25,26).

Current escape system research and development efforts within the United States Air Force (USAF) may be categorized in terms of four objectives. These are: improvement of existing escape systems, extension of the capabilities of open ejection seats, investigation of integrated cockpit/escape systems, and development of escape system concepts for vehicles operating in hypervelocity flight regimes. Examples of these efforts include upgrade of the recovery and landing systems of the F/FB-111 crew escape module, the Crew Escape Technologies (CREST) advanced development program (27,28), design of a cockpit escape module (29), and studies of escape systems for vertically and horizontally launched hypervelocity vehicles (30). Each of these efforts has a common activity, evaluation of the acceptability of the escape systems by analysis of the accelerations produced by the system. This crucial activity is carried out during both the design and test phases of escape system development. The ongoing escape system development efforts also share a second attribute, the acceleration conditions associated with each of the systems are complex including irregular waveforms and changing acceleration vector directions. These complex acceleration conditions have not and cannot be simulated with existing laboratory facilities. Therefore, assessment of the effects of these accelerations must be accomplished by using dynamic response models.

Until recently the method used by the USAF to evaluate the performance of escape systems was limited to the use of the DRI technique for the +Z axis only. Linear accelerations acting on the + and -X, + and -Y, and -Z axes were evaluated using graphs or tables, which required the fitting of the acceleration-time histories by a graphical approximation method (14,15). The method is inadequate for numerous significant reasons. First, the method is not able to evaluate the likelihood of injury unless the acceleration acts in the +Z axis. Accelerations in the X, Y, and -Z axes are either within the "zone of safety" or within the "zone of probable disablement" as shown in Figure 2.



PLATEAU	DURATION MSEC	80	126	208	360	666	1340	[illegible]
	MAGNITUDE G	12	11	10	9	8	7	6

Figure 2. Acceleration Exposure Limit Graph and Table for -Z Acceleration with Rise Times Equal to or Greater than 0.04 Sec.

Second, the graphical approximation technique is not a practical method to evaluate the complex waveforms associated with contemporary or advanced escape systems. Third, the method does not address the effects of angular accelerations and velocities. Fourth, although a computer program was developed to automate the use of the method, the automated analysis was fraught with the same limitations mentioned above as well as several others attributable to simplifying assumptions that were necessary to automate the method.

In order to overcome these limitations a more comprehensive method has been developed to evaluate the effects of escape system accelerations and velocities on the human occupant (31,32). The approach is summarized as follows: Relatively simple lumped-parameter models, which are based on the dynamic response characteristics of the human body, are used to evaluate the effects of linear acceleration components acting in the orthogonal axes of the human body. The accelerations are presumed to have their greatest deleterious effect when acting at a specific critical point. This critical point has been defined as the center of mass of the upper torso, although multiple critical points can and have been defined and evaluated. The magnitude of the responses of the dynamic response models have been related to the risk of injury. In the +Z axis the magnitude of the response has been correlated to an injury probability distribution function (11). In the other axes the risk of injury has been estimated on the basis of laboratory experiments and experience with operational escape systems. The estimates have been resolved into values corresponding to low, moderate, and high risk of major injury. The effects of the resultant acceleration condition are evaluated in terms of ellipsoidal envelopes for each injury-risk level.

This method is a first step in a more comprehensive injury assessment plan that includes strategies tailored for the escape system design and test phases. During the design phase the performance of an escape system concept will first be evaluated using a whole-body response model such as the one described above. This evaluation will be done based on the acceleration and velocity-time histories computed using models of the escape system. Where required, more refined analyses will be accomplished to evaluate the potential for specific types of injury such as might be caused by direct impact of the occupant's head or motion of the extremities. During the subsequent test phase of the escape system development, two general methods will be used. First, the effects of the linear and angular accelerations of the escape system will be evaluated using the whole-body response model and the specific injury-mode models used in the design phase. Second, specially designed and instrumented manikins (33,34,35), which have static and dynamic inertial properties as well as kinematic and kinetic response characteristics of the human body, will be used in the escape system tests. These manikins will be used to make measurements of the forces and moments acting on specific anatomical joints and skeletal structures as well as the acceleration of critical body segments such as the head.

The purpose of this paper is to describe the whole-body acceleration exposure method that has been developed to date and to provide examples of the experimental efforts accomplished to develop more accurate dynamic response model coefficients.

WHOLE-BODY ACCELERATION EXPOSURE LIMIT METHOD

The objective of the computation of dynamic response is to develop estimates of the general risk of injury at a specified critical point by analyzing measured linear acceleration and angular velocity time histories. The angular velocity of the escape system is measured and the linear acceleration is measured at a known point in the escape system coordinate system. The critical point is the point in the seat coordinate system at which the dynamic response (DR) and the associated risk of injury are computed.

If the linear acceleration at any point in the seat coordinate system is known and the angular velocity of the seat is known, then the motion of the seat is uniquely defined and the linear acceleration at any point in the ejection seat coordinate system can be calculated. The dynamic response of the body in the ejection seat is modeled by a mass, spring and damper system attached to the seat. For simplicity, the motion of the body in each orthogonal axis is assumed to be independent so that each orthogonal axis can be modeled with a different dynamic system.

Each dynamic system is accelerated by the component of the critical point acceleration that lies along the corresponding orthogonal axis. The DR for each orthogonal axis is computed from the deflection of the spring of the system. The dynamic responses of the three orthogonal axes are used to calculate a general whole-body injury risk in terms of an ellipsoidal approximation.

The equation of motion that describes the spring deflection of the dynamic system along each axis is:

$$\ddot{\delta} + 2\zeta\omega_n\dot{\delta} + \omega_n^2\delta = a_c \qquad (1)$$

where:

$\ddot{\delta}$ is the relative acceleration of the dynamic system mass with respect to the critical point.

$\dot{\delta}$ is the relative velocity of the mass with respect to the critical point.

δ is the deflection of the mass with respect to the critical point. A positive value represents compression.

ζ is the damping coefficient ratio.

ω_n is the undamped natural frequency of the dynamic system.

a_c is the critical point acceleration component that lies along the axis. The dynamic response for each axis is given by:

$$DR = \frac{\omega_n^2\delta}{g} \qquad (2)$$

where:

DR is the dynamic response of the dynamic system and g is the acceleration of gravity. The acceleration of the critical point is related to the acceleration of the measured point and the angular velocity of the escape system by the equation:

$$\vec{a}_c = \vec{a}_m + \dot{\vec{\omega}}_s x(\vec{r}_c - \vec{r}_m) + \vec{\omega}_s x(\vec{\omega}_s x(\vec{r}_c - \vec{r}_m)) \qquad (3)$$

where:

a_m is the acceleration of the measured point with respect to rest.

r_m is the position of the measured point in the ejection seat coordinate system.

a_c is the acceleration of the critical point with respect to rest.

r_c is the position of the critical point in the ejection seat coordinate system.

ω_s is the angular velocity of the seat.

$\dot{\omega}_s$ is the angular acceleration of the seat. It is computed by differentiating the angular velocity.

The general risk of injury is calculated based on the DR values for the three axes and the DR limit values. Different DR limit values are used for low, moderate and high risk.

$$\beta = \left[\left(\frac{DRX}{DRXL}\right)^2 + \left(\frac{DRY}{DRYL}\right)^2 + \left(\frac{DRZ}{DRZL}\right)^2 \right]^{1/2} \quad (4)$$

where:

DRX, DRY and DRZ are the dynamic responses for the X, Y and Z axes.

DRXL, DRYL and DRZL are the X, Y and Z DR limit values.

β is the injury-risk criterion.

The computational methods described above are applied to analyze the measured linear acceleration and angular velocitytime histories. Computational outputs include time histories for the critical point acceleration, the angular acceleration, the dynamic response (DR) for all three orthogonal axes, and the injury-risk criterion for low, moderate and high risk. The DR time histories are compared to the DR limit values for low, moderate and high risk to determine the degree of risk in each axis. The injury-risk criterion-time histories for low, moderate and high risk can be evaluated to determine the degree of risk for the whole body response. The escape system occupant is considered to have exceeded a specified injury-risk level if the injury-risk criterion has a magnitude greater than one.

MODEL DEVELOPMENT AND EXPERIMENTAL VERIFICATION

The initial approach that was used to develop each dynamic response model varied in accordance with the data that were available for the development effort. For the +Z axis the existing DRI model was adopted. Data for the -Z axis were limited to the results of experiments conducted by Shaw (5) and Schulman, et al (18) and operational experience with the B-47, B-52 and F-104 downward ejection seats. The results of the tests conducted by Shaw and the operational ejection experience were used to estimate the moderate risk-level. The data collected by Schulman, et al, were used to estimate the high-risk level. Although the symptoms of injury observed by Schulman, et al, were indefinite, the restraint system was elaborate and provided more protection than would be expected of a less encumbering restraint system that would be acceptable to operational personnel. The measurements taken by Schulman, et al, included accelerations measured on the subjects and restraint forces. These data were used to estimate the natural frequency and damping coefficient ratio of the model. The frequency was slightly lower than the DRI model and the damping coefficient was nearly identical; therefore, for simplicity the DRI model coefficients were initially adopted for the -Z axis.

Initial estimates of the X-axis model properties were derived from tests that were not specifically designed for that purpose. The data that were used were obtained from numerous reports of tests with volunteers published by the USAF, US Navy, and US Department of Defense contractors. Thus, there was a wide disparity between the experimental methods and measurements. For example, the time to peak acceleration for the +X axis data were largely in the range of 0.02 to 0.05 sec with a few data points in the range of 0.008 to 0.01 sec. The data for the -X axis were collected from tests where the time to peak acceleration ranged from 0.025 to 0.160 sec. Measurements of body response were limited in most of the experiments. In view of these limitations, the data were first analyzed using the half-sinewave approximation technique described in reference 31. The approach led to a model for the -X axis with a natural frequency of 62.8 rad/sec and a damping coefficient ratio of 0.2. Data from +X axis experiments did not provide sufficient data to estimate these coefficients with much accuracy; however, the model for the -X axis appeared to fit the available data to a reasonable degree as described in references 31 and 32.

Further confirmation of the -X axis model coefficients was obtained by analysis of the experimental data reported in reference 23. These data were analyzed using a transfer-function technique. The transfer-function technique analyzes the dynamic motion of the subject in the frequency domain. The motion of the subject in a seat is modeled by a dynamic mechanical system consisting of a mass, spring and damper attached to the seat. The seat acceleration is the base acceleration of the dynamic system and the acceleration of the subject is the mass acceleration of the system. The ratio of the system mass acceleration to the base acceleration is known as the transmissibility since it represents the transmission of motion from the base to the mass. A mathematical equation for the transmissibility can be derived by finding the Fourier transform of the equation of motion of the spring-damper system (36). The peak magnitude of the transmissibility is a function of the damping coefficient ratio and is independent of the natural frequency. Consequently, the damping coefficient ratio can be calculated from the peak magnitude of the transmissibility. The frequency where the peak magnitude occurs is a function of the damping coefficient ratio and the natural frequency. It is used to calculate the natural frequency.

The transfer-function analysis was performed on a set of data from 11 impact tests without dynamic preload, i.e., without acceleration prior to the primary impact event (23). The tests were conducted using a half-sinewave acceleration profile produced by a horizontal accelerator. The impact tests were accomplished at a level of 10 G with an impact velocity of 9.3 m/sec and a time to peak acceleration of 0.053 sec. The results of the transfer-function analysis of the upper torso acceleration indicated a mean natural frequency of 64.5 rad/sec (S.D. = 0.70) and a mean damping coefficient ratio of 0.26 (S.D. = 0.103).

Unfortunately, the results of the transfer-function analysis could not be relied upon to provide an accurate estimate of the damping coefficient ratio. Since the time to peak of the acceleration of the seat was 0.053 sec, the seat acceleration frequency spectrum could not be expected to have sufficient energy at the primary resonance of the upper torso to obtain maximum dynamic response at that frequency. Therefore, the computed value of the damping coefficient ratio could be higher than the actual value. However, the damping coefficient ratio that was obtained was considered to be within a reasonable range and was used for initial analyses.

The high risk of injury levels for the X-axis models were developed for the most part using the results of tests with human subjects conducted by Stapp (4,37) and Beeding (38,39). The low-risk levels were developed by computing the response of the X-axis model to acceleration conditions that are routinely used in research laboratories without injury. Although the research efforts were conducted with subjects who were carefully screened for pre-existing medical problems and were well restrained, this approach was considered to be conservative, since the restraining effects of the aerodynamic forces acting in the X axis were not present in most of the experimental data that were used.

Development of the Y-axis model proved to be the most difficult due to the paucity of data. Only one set of available data collected with human subjects was found to be suitable for transfer-function analysis. These data were collected during impact tests to evaluate F/FB-111 crew restraint systems (40). The data set consisted of 13 tests conducted at a deceleration level of 8 G using a trapezoidal waveform with an impact velocity of 8.84 m/sec, a time to peak acceleration of 0.022 sec and a preload due to track friction of 0.25 G. The results of the transfer-function analysis indicated a mean natural frequency of 58.0 rad/sec (S.D. = 1.7) with a mean damping coefficient ratio of 0.07 (S.D. = 0.04). The accuracy of the damping coefficient ratio is higher in this analysis than in the analysis of the X-axis data since the time to peak acceleration is shorter with respect to the natural frequency of the model. The relatively low damping coefficient ratio is probably due to the poor coupling between the seat and the subject provided by the conventional restraint harness that was used.

Injury-risk levels for the Y axis could not be established with any confidence since clear evidence of injury other than knee injury (40) and syncope (20) have not been observed under laboratory conditions. The injury-risk levels were judged on the basis of existing expert opinions and available data (17,20,40,41). The DR limit values that were established as a result of this initial analysis are shown in Table I.

Table I. Initial DR Limit Values

	DRX_L		DRY_L		DRZ_L	
	$a_{cx}>0$	$a_{cx}<0$	C.R.*	S.P.**	$a_{cz}>0$	$a_{cz}<0$
Low Risk	35	28	14	15	15.2	9
Moderate Risk	40	35	17	20	18.0	12
High Risk	46	46	22	30	22.8	15

where:

a_{cx} is the X axis component of the acceleration acting at the critical point.

a_{cz} is the Z axis component of the acceleration acting at the critical point.

*The column of limits values designated C.R. should be used if conventional restraint such as a lap belt, two shoulder straps, and crotch strap restrains the seat occupant.

**The column of limit values designated S.P. are permitted if side panels or equivalent structures are used to prevent sideward movement of the seat occupant including the occupant's head.

EXPERIMENTATION TO DEVELOP DYNAMIC RESPONSE MODELS

Available data from impact tests with human subjects provide some indication that the impact response of the human body with conventional restraint systems may be non-linear to a degree that would make attempts to use linear models to depict human response a questionable approach. Likely sources of the non-linearities include restraint slackness, the initial low stiffness of body soft tissues and restraint materials, and the effects of muscle tonus at low acceleration levels. The use of a limited set of impact test conditions and linear systems analysis methods, such as the transfer-function techniques or transient mechanical impedance techniques, can lead one to inaccurate conclusions. Therefore, a more comprehensive series of impact experiments was designed to measure the response characteristics of the human body with conventional restraint systems. The experimental designs were developed to explore a broad range of acceleration-time profiles, acceleration levels, and acceleration vector directions.

The first series of experiments were accomplished by the Armstrong Aerospace Medical Research Laboratory (AAMRL) to measure human response to impact in the -X axis (42). The tests were performed on a horizontal accelerator using six, half-sinewave impact profiles. The experimental conditions are summarized in Table II.

Thirteen volunteer subjects representing a broad range of sizes and weights participated in the test program and were exposed in random order to the impact conditions. The subjects were impacted in a seated position with a seat-back angle of 13 degrees aft of vertical. The subjects were restrained by two shoulder straps, a lap belt and crotch strap with a configuration geometry in accordance with current design practice (43). The data collected during the experiments included seat acceleration and forces, linear and angular accelerations of the head from transducers held to the subject's teeth, linear and angular acceleration of the chest from transducers mounted over the sternum, linear acceleration over the mid-thoracic spine, restraint-tiedown forces, acceleration over the lower-lumbar spine, subjective comments, and body segment motion. Means and standard deviations for selected data are shown in Table III. The restraint forces that are given in Table III are resultant values.

Table II. Conditions for -X Axis Tests

	Test Cell	A	B1	B2	C	D	E
	n	12	12	10	13	10	10
Seat Acceleration (G)	Mean	-10.97	-10.92	-10.31	-10.33	-10.39	-10.05
	S.D.	0.21	0.16	0.06	0.46	0.28	0.13
Time to Peak G (Sec)	Mean	0.017	0.021	0.029	0.038	0.065	0.117
	S.D.	0.001	0.001	0.001	0.003	0.004	C.003
Pulse Duration (Sec)	Mean	0.027	0.046	0.061	0.079	0.150	0.245
	S.D.	0.001	0.001	0.001	0.001	0.001	0.004
Velocity Change (M/Sec)	Mean	1.46	2.49	3.92	5.02	9.74	15.32
	S.D.	0.01	0.02	0.02	0.05	0.13	0.10

Table III. Summary of Data from -X Axis Impact Tests

	Test Cell	A	B1	B2	C	D	E
	n	12	12	10	13	10	10
Acceleration at Sternum (Gx)	Mean	-5.90	-10.00	-14.49	-15.67	-14.16	-9.68
	S.D	0.73	0.94	1.63	2.01	1.79	1.10
Mid-Thoracic Acceleration (Gx)	Mean	-6.73	-11.37	-17.42	-19.48	-19.70	-12.04
	S.D	1.10	1.28	1.67	2.92	3.07	1.60
Acceleration at L-4 (Gx)	Mean	-6.98	-13.17	-19.27	-18.61	-16.96	-11.85
	S.D	1.63	1.57	2.69	2.11	1.31	0.65
Head Acceleration (Gx)	Mean	-4.65	-8.02	-13.30	-15.43	-16.99	-15.52
	S.D.	0.93	1.75	4.41	8.16	3.21	3.13
Shoulder Harness Force (N)	Mean	1014	2073	3207	3389	3768	3776
	S.D.	247	297	512	641	300	663
Right Lap Belt Force (N)	Mean	1330	2860	4341	4470	4386	2998
	S.D.	219	355	426	507	627	277
Left Lap Belt Force (N)	Mean	1312	2856	4448	4515	4390	3100
	S.D.	185	335	390	543	645	284
Crotch Strap Force (N)	Mean	287	503	569	463	823	783
	S.D.	120	185	196	302	264	250
Seat X-Axis Force (N)	Mean	-974	-1068	-1201	-1134	-1068	-956
	S.D.	113	201	103	357	221	163
Seat Z-Axis Force (N)	Mean	3492	5631	7784	8167	8073	5854
	S.D.	120	694	1125	1245	1397	854

Figure 3 shows the relationship between the measured data and the response characteristics of the dynamic model developed from these data. The points encircled in Figure 3 are the mean ratios of resultant chest acceleration and the z axis acceleration of the seat for each test test condition measured at the sternum. Standard deviations about the means are indicated by crosses above and below the means. The curve that is shown is the relationship between amplitude of the response of a dynamic model and the acceleration duration of half-sinewave acceleration profiles with a constant peak acceleration. The model has a natural frequency of 56 rad/sec and a damping coefficient ratio of 0.04. The initial estimate of the natural frequency of the model was derived by transfer-function analysis and then adjusted to provide a better fit to the mean values. The damping coefficient ratio was derived by fitting the response curve to the mean acceleration values in the acceleration-duration range of 0.085 to 0.150 sec. The relatively poor fit of the model to the values at the acceleration durations of 0.027 and 0.046 set was accepted as due to the relative ineffectiveness of the restraint geometry and soft-tissue deformation. Similar dynamic response characteristics were seen in the chest response measured over the mid-thoracic spine although additional amplification of about 20 per cent was observed due to the dynamic response of the thoracic volume. The response of the head and neck also reflected the influence of the frequency response of the upper torso at the shorter impact durations as well as the lower frequency response of the head/neck seen in the data reported by Ewing (24) at the longer durations. Restraint-tiedown forces also reflected the influence of the dynamic response characteristic of the torso. The severity of the impacts as indicated by subjective response questionnaires correlated well with the amplitude of the measured acceleration and forces.

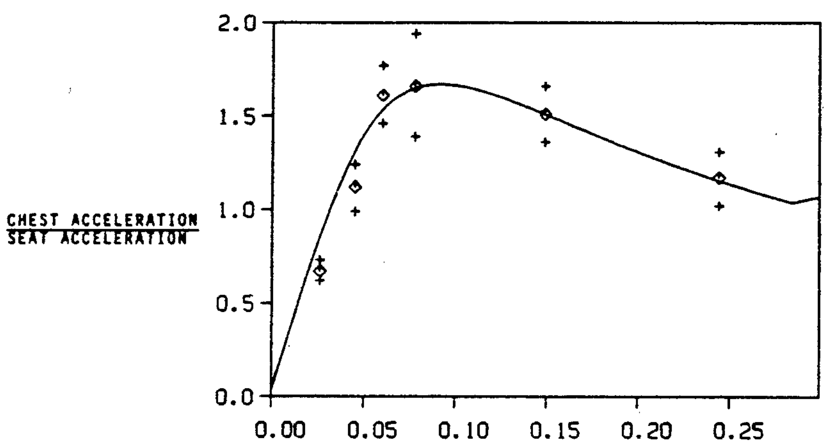


Figure 3. Ratios of Resultant Chest Acceleration and Seat Acceleration for Each -X Axis Impact Test.

The most recent series of experiments conducted to refine the dynamic response models was conducted to measure the human response to impact in the -Z axis (44). These tests were also performed on a horizontal accelerator using six, half-sinewave impact profiles. The test conditions are summarized in Table IV. Twelve volunteers participated in the tests. Eight to 12 subjects were restrained in a seated position using two shoulder straps, a lap belt with crotch strap, and leg straps. The seat back was parallel to the acceleration vector. The subjects grasped two ejection-initiation handles that were instrumented to measure tension forces. The measurements also included seat acceleration and forces, restraint-tiedown forces, head and chest linear and angular accelerations, subjective comments, and body segment motion.

Means and standard deviations for the primary measurements are given in Table V. Acceleration measured on the head and chest reached maximum values when the acceleration profile duration was 0.082 sec. The head and chest accelerations were less than the seat accelerations when the acceleration profile duration was 0.030 sec.

Figure 4 shows mean ratios of the resultant chest acceleration and seat acceleration for each test condition. Corresponding standard deviations are also plotted about the mean values. The curve shown in Figure 4 is the response of a dynamic model to half-sinewave acceleration profiles with a constant peak acceleration level. The natural frequency of the model that best fits the data is 47.1 rad/sec with a damping coefficient ratio of 0.24. The natural frequency and the initial estimate of the damping coefficient ratio were derived by transfer-function analysis.

Table IV. Conditions for -Z Axis Impact Tests

	Test Cell	L	M	N	O	P	Q
	n	11	12	11	10	8	12
Seat Acceleration (G)	Mean S.D	-10.41 0.09	-12.38 0.18	-11.43 0.16	-10.69 0.06	-10.15 0.08	-10.26 0.07
Time to Peak G (Sec)	Mean S.D	0.017 0.001	0.026 0.005	0.038 0.001	0.063 0.001	0.105 0.007	0.114 0.001
Pulse Duration (Sec)	Mean S.D	0.033 0.001	0.065 0.001	0.085 0.001	0.155 0.001	0.213 0.004	0.252 0.001
Velocity Change (M/Sec)	Mean S.D	1.47 0.02	3.97 0.04	4.98 0.05	9.85 0.04	12.29 0.09	15.40 0.07

Table V. Summary of Data From -Z Axis Tests

	Test Cell	L	M	N	O	P	Q
	n	11	12	11	10	8	12
Acceleration at Sternum (Gz)	Mean S.D	-7.03 1.47	-12.76 2.12	-13.50 1.08	-13.87 1.60	-12.56 2.18	-10.00 0.98
Head Acceleration (Gz)	Mean S.D.	-6.68 0.89	-17.23 1.15	-18.54 1.64	-18.46 1.58	-15.46 1.39	-12.33 1.39
Shoulder Harness Force (N)	Mean S.D.	868 165	2006 489	2116 477	2116 468	2336 503	1982 370
Right Lap Belt Force (N)	Mean S.D.	1190 160	3017 402	3319 318	3447 243	3054 344	2510 262
Left Lap Belt Force (N)	Mean S.D.	1121 150	3078 404	3287 210	3418 314	3210 442	2528 265
Crotch Strap Force (N)	Mean S.D.	460 242	1862 741	2001 731	2052 673	1747 712	1439 517
Right Leg Restraint Force(N)	Mean S.D.	627 93	1074 227	1046 195	1025 135	962 115	846 118
Left Leg Restraint Force (N)	Mean S.D.	617 84	1043 185	1026 165	1004 163	926 122	836 119
Right Handle Force (N)	Mean S.D.	338 99	559 165	522 138	569 144	644 131	531 137
Left Handle Force (N)	Mean S.D.	353 98	579 125	657 163	745 208	829 180	677 163

A two-degree-of-freedom model was used to study the response of the head. The best fit, which is shown in Figure 5, was obtained with both the lower degree of freedom and upper degree of freedom having natural frquencies of 47.1 rad/sec and damping coefficient ratios of 0.24. The ratio of the mass of the upper degree of freedom to the mass of the lower degree of freedom is 0.3.

As in the case of the study of the human response to -X axis acceleration, the restraint-tiedown forces also reflected the response of the torso to the impact conditions.

Since the model coefficients found from the -Z axis impact tests are somewhat different than the DRI model coefficients used in the initial dynamic response model for the -Z axis, new DR limit values were computed. The low-risk limit was computed from the test results using a single-degree-of-freedom model. This value is 13.4. A moderate-risk value of 16.5 was computed using the maximum allowable acceleration condition of MIL-S-9479B. A high-risk value of 20.4 was computed using the worst-case impact condition tested with volunteers by Schulman, et al. The resulting acceleration exposure limit curves for half-sinewave acceleration profiles is shown in Figure 6.

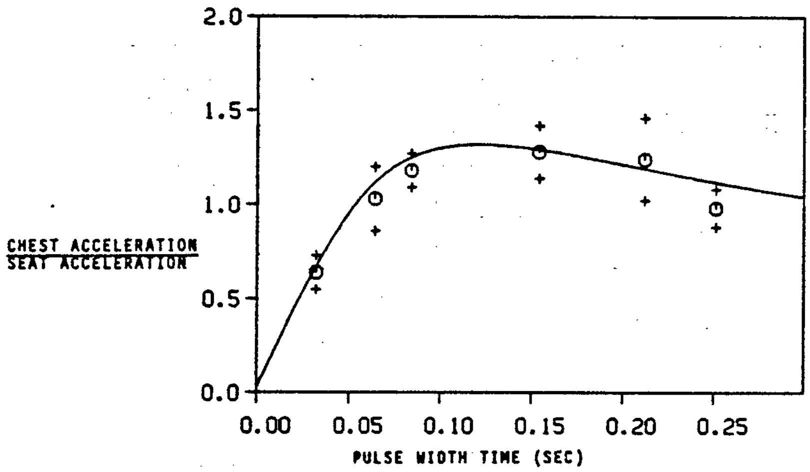


Figure 4. Ratios of Resultant Chest Acceleration and Seat Acceleration for Each -Z Axis Impact Test.

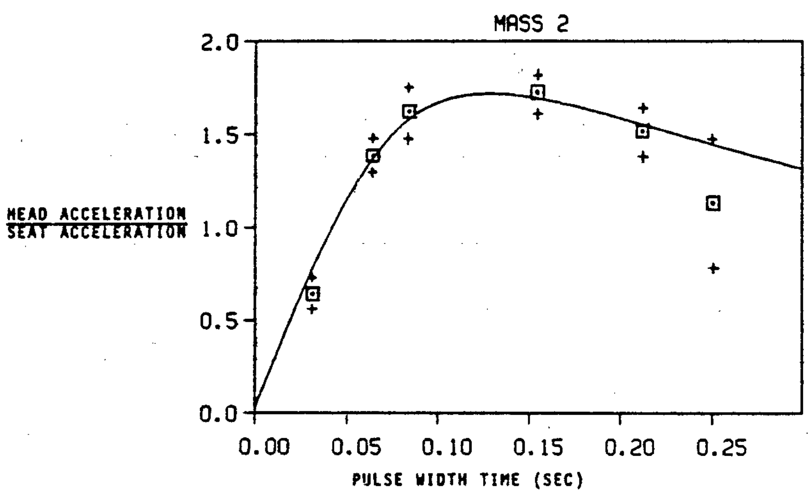


Figure 5. Comparison of the Response of a Two-Degree-of-Freedom Model to Experimental Measurements of Head Acceleration.

DISCUSSION

The experiments that have been conducted by the AAMRL to measure human body impact response over a broad range of acceleration conditions have shown that linear system approximations of the measured data are reasonable. The acceleration attenuation expected in the short-duration acceleration regime is seen in the experimental results as well as the amplification of the response that was expected at the resonant frequency. Subjective estimates of the relative severity of the impact conditions were found to generally correspond to the measurement of body accelerations. The experimental results tended to also confirm earlier estimates of the natural frequency of the whole body response. Stech and Payne estimated that the primary resonance affecting human tolerance to impact in the -X axis was 60.8 rad/sec with a damping coefficient of 0.23 (11). However, these estimates had been based upon limited observations over a relatively narrow range of acceleration-time histories, and the attenuation of the human response for short-duration profiles had not been clearly demonstrated with human subjects.

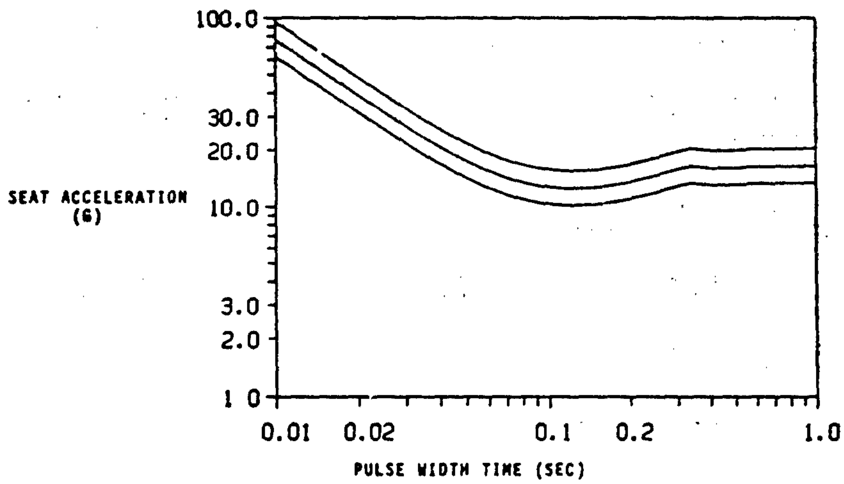


Figure 6. Exposure Limit Curves for Half-sinewave Acceleration in the -Z Axis.

The experimental results of the tests of humans in the -X axis showed a small difference between the initial estimate of the natural frequency affecting whole-body tolerance and the experimentally determined value, 62.8 versus 56.0 rad/sec respectively. The difference between the initial estimate of the damping coefficient ratio and the experimental result is more significant, 0.2 versus 0.04, and suggests that the original computations to estimate the injury-risk levels should be reaccomplished. This work is in progress using additional data recently recovered from experiments conducted using the Daisy Track impact facility at Holloman Air Force Base.

The experimental results from the -Z axis tests show a similarly small difference between the natural frequency initially estimated and that experimentally derived, 52.9 rad/sec versus 47.1 rad/sec, but this difference also has little practical effect. The difference between the damping coefficient ratio originally assumed for the Z-axis, 0.224, and the experimentally demonstrated value, 0.24, are within the experimental error. The most important result of the test results, for the -Z axis is that they provide a firmer data base for the dynamic response model, which in turn provide a method to revise earlier estimates of the injury-risk levels.

Additional experimental efforts are currently being planned to investigate human body response to impact in the Y axis. These efforts will include tests with conventional restraint harnesses and full-body support panels since the body support and restraint configuration will have a large effect on the model properties.

The primary emphasis of the experimental efforts conducted recently in the United States has been on measuring the human response to impact vectors along the three orthogonal axes. However, research is now being focused on the effects of impact vectors in other axes. Experiments recently accomplished at the AAMRL by Perry and Brinkley have investigated the effects of short-duration acceleration directed in the +Z axis and in axes 10, 5, -5 and -10 degrees off of the Z axis in the mid-sagittal plane. These experiments have not shown significant changes in the frequency response of the volunteer subjects as a function of these angles at acceleration levels up to 10 G.

Future analytical efforts will be focused on developing methods to include the effects of both inertial and aerodynamic forces on occupants of ejection seats. Rather simplistic analyses have shown that the aerodynamic forces acting on an ejection seat occupant during ejection may have beneficial effects as well as adverse effects such as limb flail. For example, the aerodynamic drag force acting on the occupant's helmet during deceleration of the seat and its occupant may effectively restrain the occupant's head and neck from otherwise violent forward motion. However, if the seat yaws excessively during acceleration the aerodynamic forces may cause an adverse effect since the head will be driven off the headrest by the aerodynamic forces. These types of effects cannot be quantitatively evaluated using existing analytical approaches since the aerodynamic flow field is incompletely defined, but it is known that it is not uniform (45).

The practicality and effectiveness of using the exposure limit method that has been described within this paper is now being evaluated within the laboratory and also within escape system development programs. It has been used to analytically evaluate the effects of seat occupant weight on the performance of the ACES II ejection seat and to evaluate the test data from ejection tests of several escape systems. The method has also been used throughout the development of the Crew Escape Technologies ejection seat demonstrator and in the exploratory of several hypervelocity escape system concepts. This combination of laboratory, field test, and contractor use has been critical to the continued development and improvement of the method. This interactive process has also been vital to prioritizing the laboratory experimental efforts and adjusting the escape system test methods.

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CHOCS A L'OUVERTURE LORS DES EJECTIONS A GRANDE VITESSE ? QUELLES NORMES ?

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RESUME

L'évolution des conditions d'éjection des pilotes d'avions de combat amène à envisager le domaine grande vitesse, basse altitude comme une probabilité non négligeable. Si les problèmes liés au souffle aérodynamique et à la stabilisation du siège constituent les facteurs les plus pénalisants, il peut également exister un risque traumatique lié à l'ouverture du parachute.

Une étude portant sur des tirs de compatibilité du siège MK 10 avec différents avions de combat a été réalisée sur des essais au rail dynamique. Les résultats montrent une augmentation importante des accélérations + Gz enregistrées à l'ouverture du parachute principal.

L'analyse biomécanique du choc met en évidence le rôle des différentes phases de l'ouverture. Ces données amènent à envisager le problème de la normalisation et des critères utilisables.

1. - INTRODUCTION

Les conditions de combat d'un avion tactique moderne l'amènent à évoluer de manière prolongée et répétée en très basse altitude à grande vitesse. L'introduction des systèmes de guidage inertiel et de suivi de terrain automatique a permis de rendre ce type d'évolutions parfaitement opérationnel en toutes circonstances. Toutefois, dans ces conditions, la probabilité d'avoir à tenter une éjection au cours d'une mission de combat est loin d'être négligeable.

Avec les sièges modernes munis de fusées, les risques des éjections grande vitesse ne résident généralement plus au niveau de l'impact avec les structures de l'avion. Le passage de la dérive est assuré largement, même à l'extrême limite du domaine. En revanche, les effets du souffle aérodynamique et les problèmes liés à la stabilité du siège pendant la phase balistique ont largement été évoqués. Ces dernières années, d'importants efforts technologiques ont été réalisés dans ce domaine. Ils ont conduit à la mise en oeuvre de concepts de protection qui, sans régler définitivement tous les problèmes, améliorent notablement les chances de survie du pilote lors des éjections grande vitesse basse altitude.

L'importance des aspects liés au souffle aérodynamique en matière de risque traumatique à l'éjection contribue sans doute à masquer un risque pourtant classique, celui du choc à l'ouverture de la voilure principale. Ce risque a été reconnu de longue date à l'origine de traumatismes mortels lors de l'éjection.

Si l'on considère le vaste domaine d'emploi des voilures de siège éjectable, du zéro-zéro jusqu'à 600 Kt et même plus, on conçoit bien que l'optimisation des caractéristiques d'ouverture n'est pas chose aisée. Ces voilures sont donc obligatoirement le fruit de compromis. En règle générale, elles se gonflent très rapidement, en une à deux secondes, permettant un fonctionnement correct en toutes circonstances. Lors des éjections en grande vitesse, ces caractéristiques ont amené à constater des chocs à l'ouverture d'intensité très élevée lors de tirs de siège MK 10.

2. - METHODES

Depuis de nombreuses années, le Service Technique des Programmes Aéronautiques équipe les avions de combat français de sièges britanniques Martin-Baker. Ces sièges sont fabriqués sous licence en France par la SEMMB. Le Centre d'Essais en Vol a pour mission d'effectuer des tirs de compatibilité avec les aéronefs sur lesquels seront montés ces équipements. La plupart de ces tirs sont effectués sur le rail dynamique du Centre d'Essais des Landes.

2.1. - Le rail dynamique :

Ce rail a une longueur totale de 2000 m.

Une maquette de la partie avant du fuselage de l'aéronef testé est montée sur des patins adaptés au rail. Cette maquette abrite le système de sauvetage et les installations de mesure. Elle supporte les efforts dus à l'accélération des véhicules pousseurs-freineurs. Ceux-ci sont constitués par le véhicule pousseur-freineur GECKO pour la poussée et la stabilisation en vitesse, équipé de deux augets de freinage hydrodynamique et des étages additionnels de poussée qui sont utilisés selon le type de l'essai.

2.2. - Moyens de mesure et d'observation :

Les mesures sont assurées par deux installations de télémesure embarquées.

La première est installée à l'arrière du fuselage dans un caisson fixé sur le véhicule pousseur. Cette installation a pour but :

- de déterminer la cinématique du véhicule ;

- d'apprécier l'environnement vibratoire dans les directions verticale et transversale ;

- de transmettre en redondance un "top" de synchronisation avec la mise à feu du siège ;

- de mesurer les accélérations suivant les trois axes au point d'attache supérieure du siège.

La seconde est située dans le mannequin. Elle enregistre les paramètres de fonctionnement du siège ainsi que les accélérations au niveau du thorax du mannequin suivant les trois axes X, Y, Z.

Les moyens de mesure optique se décomposent en différentes fonctions, observation générale, observation particulière, observation depuis le véhicule et enfin trajectographie. Les caractéristiques de ces moyens sont résumées au tableau I.

2.3. - Mannequin :

Les mannequins utilisés sont du type ALDERSON VIP 50. Trois tailles différentes sont utilisées selon les essais, 98 percentile, 50 percentile et 3 percentile.

3. - RESULTATS

L'étude porte sur 30 tirs de compatiblité du siège MK 10 réalisés entre 1979 et 1988 à l'occasion de différents programmes aéronautiques (Mirage F1 CR, Mirage F1 B, Mirage 2000, Rafale, Alpha-jet). Les vitesses d'éjections s'étendaient de 587,8 KEAS (302,4 m/s) à 61 KEAS (31,4 m/s). Le choc à l'ouverture de la voilure principale a pu être analysé dans 27 cas.

Avant de considérer les résultats d'ensemble, il convient d'illustrer l'intensité du choc en grande vitesse avec un exemple précis.

3.1. - Présentation d'un tir :

Le tracé présenté à la figure 1 a été enregistré à l'occcasion d'un tir réalisé à 578 Kts. On peut observer que l'accélération Gz maximale est largement supérieure à 25 G (saturation du capteur accélérométrique) pendant une durée qui excède 100 ms.

Compte tenu des données existantes dans la littérature et bien qu'il soit parfois hasardeux d'extrapoler à l'homme les résultats obtenus avec un mannequin, on peut penser que le risque traumatique dans ce cas aurait été particulièrement sévère.

Il est également intéressant de considérer les paramètres détaillés de ce tir, présentés au tableau II. On observe que la vitesse sur trajectoire du siège au moment du déverrouillage retardé est relativement élevée (132 m/s) par rapport à la moyenne (environ 120 m/s). Ceci témoigne d'un travail insuffisant du parachute stabilisateur. D'autre part, la durée d'ouverture du parachute (Délai entre le fonctionnement du mécanisme de déverrouillage retardé et premier grand diamètre de la voile, est très brève (610 ms, 350 entre la tension des suspentes et le grand diamètre). En quelque sorte, la voilure s'est "trop bien ouverte".

Ceci montre bien, que pour une éjection techniquement réussie, des variations minimes dans les paramètres critiques peuvent entraîner des chocs à l'ouverture sévères, susceptibles d'entraîner eux mêmes des blessures graves, éventuellement la mort du pilote.

3.2. - Valeurs moyennes

Le tableau III présente les valeurs moyennes des accélérations Gz relevées à l'ouverture pour trois classes de vitesse d'éjection (supérieure à 450 KEAS, entre 450 et 150 KEAS, inférieure à 150 KEAS).

Si l'on considère les durées d'accélérations supérieures à 100 ms, pour les éjections à grande vitesse, on observe que les valeurs moyennes d'accélérations + Gz sont largement supérieures à celles obtenues avec les vitesses plus faibles. Les valeurs relevées pour la classe 150 - 450 KEAS sont pour leur part relativement proches de ce qui résulte de l'utilisation de parachutes classiques (sportifs ou militaires). Notons toutefois que la plupart des tirs à grande vitesse ont été réalisés avec des mannequins 98 percentile, alors que beaucoup de tir à faible vitesse ont utilisé des mannequins à 50 ou 3 percentile.

Les valeurs maximales observées en pic et les valeurs relevées à la tension des suspentes accroissent encore les différences entre les tirs grande vitesse et les deux autres classes.

La réglementation française sur l'intensité maximale admissible du choc à l'ouverture prévoit une limite de 12 G. Cette règlementation est, bien sûr, uniquement appliquée aux parachutes militaires et sportifs et aux voilures de sauvetage classiques. Cette norme, déjà très critiquable dans ce cadre se révèle donc totalement inadaptée au problème du choc à l'ouverture lors des éjections. Ceci amène à poser une question: Faut-il et est-il possible de normaliser les chocs à l'ouverture des voilures de siège éjectable ?

4. - <u>NORMALISATION DES CHOCS DE L'OUVERTURE DES PARACHUTES.</u>

Avant d'aborder cette discussion, il parait opportun d'effectuer un bref rappel sur l'analyse biomécanique des effets du choc à l'ouverture.

4.1. Analyse biomécanique du choc à l'ouverture :

Il existe relativement peu de données expérimentales précises sur les chocs à l'ouverture des parachutes lors des éjections. En revanche de nombreux travaux se sont attachés à préciser la direction et l'amplitude des accélérations subies par des parachutistes utilisant des parachutes militaires ou sportifs.

Diverses approches expérimentales ont été tentées, en particulier par CALL et coll. ainsi que par REID (2,7). Les résultats obtenus lors de ces études ont permis de préciser les notions d'accélération subies par le parachutiste lors de l'ouverture. En utilisant une technique de télémesure pendant le saut, les signaux de jauges de contraintes et d'accéléromètres linéaires, placés selon les trois axes du corps au niveau du thorax, ont pu être enregistrés pour différents sujets et plusieurs types de parachutes. Les résultats obtenus montrent que la valeur moyenne du pic d'accélération + Gz atteint 7.4 G, avec une très grande variabilité (de 2,7 à 15 + Gz). La valeur moyenne de pics d'accélération transverse Gx était de 6.8 Gx avec des valeurs extrêmes de 2.7 à 14 Gx.

L'analyse détaillée des forces qui s'exercent, surtout au niveau du rachis du parachutiste, constitue une démarche essentielle pour comprendre les effets du choc à l'ouverture.

Les forces crées par le développement de la voilure sont transmises au niveau de la jonction élévateurs-harnais qui se trouve, pour la plupart des parachutes en service, entre la base du cou et la jonction acromio-claviculaire. Pour ce qui concerne le rachis, on constate donc que l'axe joignant les raccordements de la voilure sur le harnais passe très près de la charnière cervicodorsale.

Lors de l'ouverture du parachute, deux évènements sont à considérer

- D'un côté de l'axe précédemment défini, les forces d'inertie s'exercant sur l'ensemble tête-colonne cervicale par rapport au thorax font apparaître un couple qui entraîne une hyperflexion de la tête sur le thorax.

- Le thorax et le bassin du parachutiste sont, en quelque sorte, enveloppés par le harnais du parachute. En raisonnant en termes d'inertie, les forces s'appliquant par l'intermédiaire des sangles basses du harnais, cuissardes et fessière, vont mettre la rachis dorsal et lombaire en compression. L'effet est donc celui des accélérations + Gz, comparable par exemple au départ du siège éjectable.

Parallèlement à cet aspect biomécanique, les observations de traumatologie du choc à l'ouverture, bien que relativement rares, amènent à considérer deux types de lésions distinctes : les lésions de la colonne cervicale et les fractures du rachis dorsal au niveau de D8-D9. Il semble donc logique de correler les aspects biomécanique et traumatologique.

Deux points sont à souligner :

- Dans tous les cas, l'état de la musculature paravertébrale, contraction ou relaxation, semble jouer un rôle important dans l'apparition de lésions.

- Pour ce qui concerne les éjections de pilotes d'avions de combat, un facteur aggravant nouveau apparait au niveau du rachis cervical, avec l'utilisation de dispositifs optroniques montés sur le casque. Ceux-ci, en augmentant la masse du système tête cou et, éventuellement, en déplaçant le centre d'inertie de la tête, vont contribuer à la création de couples encore plus importants.

Compte tenu des résultats expérimentaux obtenus lors des éjections grandes vitesses, on doit alors considérer que le risque traumatique au niveau du rachis cervical constitue dans ces conditions un facteur très pénalisant pour la réussite de l'éjection. Encore faudrait-il disposer de critères précis permettant d'évaluer ce risque avec certitude.

4.2. - Critères de lésion et normalisation :

Le préalable à toute démarche de normalisation est d'établir des critères de lésions fiables. Dans ce domaine, de nombreux travaux ont été réalisés, en particulier pour ce qui concerne la traumatologie des accidents d'automobile.

Toutefois, les différents critères définis dans ces conditions ne sont pas forcément applicables directement au problème du choc à l'ouverture.

A l'heure actuelle, pour ce qui concerne les parachutes d'une manière générale, la procédure d'homologation comporte une série de lancers mannequins et des sauts humains.

Parmi les critères retenus dans la norme existant en France, il est spécifié que l'effort maximum à l'ouverture, mesuré au niveau des élévateurs, ne doit pas dépasser 1200 daN. Avec une masse suspendue de 100 kg, cela correspond approximativement à un pic d'accélération de 12 G. Toutefois, la norme ne spécifie aucun critère temporel associé à la notion d'intensité.

L'élaboration d'une norme plus "compréhensive" implique donc en premier lieu l'intégration du paramètre temps aux critères de jugement. Il est en effet bien établi depuis les nombreux travaux menés à la suite de STAPP que des accélérations bien plus élevées que 12 G peuvent être supportées sans dommage par l'organisme humain à condition d'avoir des durées très brèves. Par contre, dès que la durée d'application augmente, l'intensité tolérable décroît très rapidement, ce qui constitue une donnée très classique. Une excellente revue de ce problème a été réalisée par SNYDER (8).

Le problème consiste donc à déterminer, d'après les différentes courbes de tolérance établies en fonction du temps, une enveloppe du choc à l'ouverture maximal supportable sans dommage par l'organisme humain. Cette enveloppe devrait prendre en compte non seulement l'intensité des accélérations et leur durée, mais aussi la notion de jolt (dérivée de l'accélération). De plus, une telle enveloppe devrait également couvrir les deux aspects évoqués pour la biodynamique du choc à l'ouverture avec les contraintes au niveau du rachis cervical et dorsal.

On peut donc considérer aisément que l'établissement d'une norme répondant à ces critères est relativement complexe. De nombreux auteurs et en particulier EWING, se sont attachés à définir les limites de tolérance de l'ensemble tête-cou pour les accélérations Gx (3,4). Certaines études (2) ont même précisé la réponse de la tête lors des ouvertures de parachutes. Toutefois, l'interprétation et la transposition de ses données en vue de l'élaboration d'une norme reste difficile.

La modélisation mathématique de la dynamique des segments corporels soumis à des accélérations complexes constituent sans aucun doute une approche intéressante. HUSTON et KAMMAN ont appliqué de tels modèles au choc à l'ouverture des parachutes (5). Une telle approche, couplée à la modélisation du choc à l'ouverture selon les caractéristiques du parachute (6), peut amener un jour nouveau sur le problème.

Toutefois ces modèles sont essentiellement descriptifs et ils ne pourraient éventuellement répondre qu'à une partie du problème. Ils fournissent cependant un outil précieux, car la mesure directe de données biomécaniques, sur sujet humain lors d'un saut réel, présente de sérieuses contraintes et est difficilement applicable en routine.

Le problème de la représentativité des mannequins pour les études du choc à l'ouverture a été abordé il y a quelques années par BALDOCK (1). Sur ce point, il faut noter les efforts réalisés pour doter les mannequins anthropomorphiques d'une plus grande représentativité, en particulier vis à vis des accélérations + Gz.

En dépit de tous ces éléments, il faut bien reconnaître qu'il n'existe pas de norme simple, de mise en oeuvre facile, susceptible d'être universellement acceptée, qui puisse à l'heure actuelle s'appliquer au choc à l'ouverture des parachutes.

La normalisation du choc à l'ouverture de parachute est un élément indispensable pour l'homologation des voilures sportives et militaires. Pour ce qui concerne les parachutes de sauvetage et plus encore les voilures de siège éjectable dans les conditions grande vitesse et basse altitude, on peut s'interroger sur le bien-fondé d'une telle démarche.

La mise en oeuvre de ces voilures correspond à des situations exceptionnelles ou de toute façon la vie du pilote est en jeu dès le départ. Compte tenu de la multiplicité des facteurs d'agression, ceci apparaît particulièrement vrai pour les éjections en limite de domaine.

Il faut toutefois considérer que les différentes phases de l'éjection constituent une chaine et qu'une éjection n'est totalement réussie que lorsque le pilote est au sol, sans présenter de lésion traumatique.

Les résultats obtenus lors des tirs de compatibilité en grande vitesse montrent que de faibles variations sont susceptibles d'entrainer des chocs à l'ouverture difficilement supportables par l'organisme. Dans ces conditions le fait d'avoir un objectif précis et raisonnable de limitation de choc à l'ouverture constitue un élément qui ne peut que contribuer à la réussite des éjections.

CONCLUSIONS

Les éjections grande vitesse en basse altitude demeurent des situations ou le risque traumatique est important. Les résultats expérimentaux obtenus montrent qu'à côté des agressions classiques (propulsion du siège, souffle aérodynamique), le choc à l'ouverture de la voilure principale est hautement susceptible d'être à l'origine de traumatismes graves, voire mortels.

Il semble nécessaire de préciser les limites de tolérance du corps humain et en particulier du rachis cervical, vis-à-vis de ce type d'agression. Cette démarche devrait permettre d'établir une norme de référence pour les chocs à l'ouverture des parachutes.

Il apparaît en tout cas souhaitable que la prévention de chocs à l'ouverture excessivement élevés soit examinée avec attention par les constructeurs de sièges. A cet égard, les progrès récemment introduits dans la stabilisation des sièges éjectables constituent indéniablement un aspect positif dans ce sens.

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MOYENS DE MESURE OPTIQUE

Définition des Caméras	Nombre de caméras	Type de film (mm)	Cadence (i/s)	Focale (mm)	Position de la Caméra par rapport au rail
Observation Générale	5	35 35 16 16 16	400 400 500 500 150	500 500 150 150 75	3/4 Arrière 3/4 Avant perpendiculaire à l'axe d'éjection
Observation particulière	7 1	35 35	1000 1000	150 1000	perpendiculaire à l'axe d'éjection Dans l'axe du rail
Observation depuis le véhicule	3 1	16 16	500 500	9,8 5	sur Pods interne
Trajectographie	2 2	ciné "C" 35	30 100	500 50	3/4 Arrière et Avant 3/4 Arrière et Avant

TABLEAU N° 1 : MOYENS DE MESURE OPTIQUE UTILISES AU RAIL D'EJECTION DYNAMIQUE.

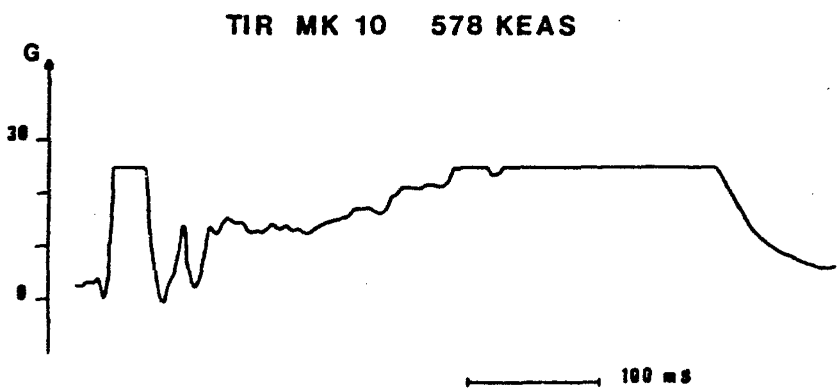

Figure N° 1 : Tracé des accélérations + Gz mesurées au niveau du thorax. du mannequin lors de l'ouverture du parachute.

TIR SIEGE MK.10

VITESSE D'EJECTION 578 KEAS

MANNEQUIN	98 PERCENTILE
MASSE	106,5 kg
DUREE OUVERTURE	610 ms
DUREE GONFLEMENT DE VOILURE	360 ms
VITESSE AU MDR	132 m/s
VITESSE A LA TENSION SUSPENTE	114 m/S
Gz A LATENSION SUSPENTE	25G / 23ms
Gz MAXI A L'OUVERTURE	> 25G pendant 200ms
VITESSE SUR TRAJECTOIRE AU GRAND DIAMETRE	25m/s

TABLEAU N° 2 : Caractéristiques détaillées du tir MK 10 à 578 KEAS.

MOYENNE DES CHOCS A L'OUVERTURE
SIEGE MK 10 - VOILE GQ 1000

MESURES de Tirs / Vitesse D'éjection	Nombre de tirs	Gz Tension Suspentes	Gz Max	Gz Max >100ms
VE > 450 KEAS	15	22 ±5	19,2 ±4	14,7 ±4,6
450>VE>150 KEAS	5	10,3 ±2,5	9,8 ±2,5	6,9 ±3,7
VE < 150 KEAS	8	4,3 ±2,3	4,3 ±2,2	2,8 ±1,8

TABLEAU N° 3 : Valeurs moyennes des chocs à l'ouverture obtenus pour différentes classes de vitesses.

DEVELOPMENT OF AN EJECTION SEAT SPECIFICATION FOR A NEW FIGHTER AIRCRAFT

by

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Introduction

The development of a new aircraft brings with it the opportunity to incorporate improvements, and new features, in the design of the escape system that experience with previous systems has shown to be necessary. Just such an opportunity occurred with the announcement of the development of the European Fighter Aircraft. The United Kingdom input to the specification of the ejection seat for this aircraft was derived from accident experience and from analysis of ejection test data from previous marks of ejection seat. The aim of this paper is to discuss the problem of impairment of consciousness on ejection, the rationale for improvements in ejection seat stability, and measures taken to improve ejection seat headbox impact attenuation.

Accident Investigation

The purposes of investigating the use of ejection seats are to check that the ejection seat has functioned correctly, and to attempt to determine whether the operation of the escape system has contributed to any injuries that the aircrewman has suffered. Ejections fall into two groups: those within and those outside the safe escape envelope. Quantification of the ejection conditions, a task eased by the increasing use of accident data recorders, allows an estimate to be made of how close an out of envelope ejection is to the safe escape boundary. Subsequent computer reconstruction, using iterations of different escape conditions, can refine these estimates. Use of the computer model also permits the testing of changes in time and drogue and parachute performance on escape system behaviour. Thus potential improvements can be checked cheaply and quickly without immediate recourse to expensive experimental ejection test shots. Use of such techniques has produced requirements for progressive increases in the size of ejection seat safe escape envelopes. Royal Air Force ejection experience has however shown the following to be of concern on otherwise 'within envelope' escapes:

a) Impairment of consciousness

b) Ejection seat instability

c) Helmet/parachute riser interactions

d) Head/headbox interactions

Impairment of consciousness

As a result of the work conducted at the Royal Air Force Institute of Aviation Medicine in support of AGARD AMP Working Group 11, a review was conducted on the incidence of impairment of consciousness on 'within envelope' ejections between 1968-1981 (Anton 1984). Impairment was taken as referring to a condition where some degree of disturbance of cerebral function, considered to have been caused by acceleration, has occurred, but where the circumstances of the accident preclude the precise definition of the alteration of consciousness. In the past it has been the custom to ask the Medical Officer reporting on the accident, to assess the injured crewmember as to whether he was comatose, or had suffered a degree of concussion. This approach was unsatisfactory as it resulted in a series of records where the degree of head injury could not be objectively compared between accidents, due to the lack of commonality of assessment by the recording Medical Officers. Accordingly a new system was devised based upon an assessment of the duration of post traumatic amnesia. This could be assessed from the time history of the accident, the subject's documented statement about the accident, the clinical notes and, where necessary and possible, by re-interviewing the subject. A further value of using post traumatic amnesia as an index is that it is related to the degree of cerebral damage, (Russell, 1932, 1971) as well as being a predictor of subsequent recovery from head injury (Jennett & Teasdale 1981). For the purposes of the study, the duration of post traumatic amnesia was defined as the duration of absence of memory from the initial event, to the return of continuous memory. Thus 'islands of memory' were recorded within the duration of the post traumatic amnesia.

With the above provisos, six survivors from two hundred and thirty seven within envelope ejectees (2.5%) were assessed as having suffered a head injury, as evidenced by a post traumatic amnesia lasting from one to two minutes, to four hours. Eight fatalities were also noted in this series, one of which showed unequivocal evidence of impairment of consciousness, three others exhibiting circumstantial evidence of the same, to give an overall incidence estimate of 4.2%. The probable cause of the impairment of consciousness in the survived and in the fatal groups is shown in Tables 1 & 2. It can be seen that ejection forces, a loose term embracing ejection seat instability and drogue and parachute forces, and including both direct and inertial trauma, were deemed to be responsible for half of the impairment of consciousness related fatalities and a third of the injuries in the survived group.

Table 1

Probable Cause of Impairment of Consciousness in Survived Group

Through Canopy Ejection	1
Hit Head on Ground	2
Ejection Forces	2
Head/Headbox contact	1

Table 2

Probable Cause of Impairment of Consciousness in Fatal Group

Through Canopy Ejection	2
Ejection Forces	2

The incident of impairment of consciousness, and fatality related impairment of consciousness, and fatality related impairment of consciousness, has not been documented since 1981, but unofficial estimates indicate that the incidence is essentially unchanged despite the virtual elimination of through canopy ejection.

Ejection seat instability

It has been known for some time that unless ejection seats are stabilised they have a tendency to roll, and/or yaw, during rocket burn, shortly after initial entry into the airstream. As a result of this instability, subsequent drogue and parachute deployment vectors can be markedly 'off axis', giving rise, on occasion, to unacceptably high forces on the seat occupant. The following two cases (Anton, op cit) show examples of lateral parachute extraction, thought to be due to ejection seat instability, where concern was expressed that the crewman may have been incapacitated as a result of forces experienced during ejection.

Case No 185.

This aircraft was one of a pairs formation. The subject aircraft crew had been briefed to do a loose article check at some stage of the flight. At 420kts in company with the first aircraft, the subject aircraft rolled a full 360 degrees, and then rolled again. In the second roll it pitched nose down, whilst inverted. The canopy was seen to detach, and a flash, possibly due to the rocket motor of the ejection seat was seen. The instructor from the rear seat of the subject aircraft was recovered, drowned, beneath an apparently normally deployed parachute. He had not accomplished any post ejection drills. Investigation showed that the aircraft was yawing markedly at the time the instructors ejection was initiated. Reconstruction and computer simulation indicated that the ejection was probably 'within envelope'. Investigation also revealed evidence of lateral parachute extraction. At autopsy there was evidence of bruising in the right paravertebral muscles although there was no evidence of damage to the brain or spinal cord.

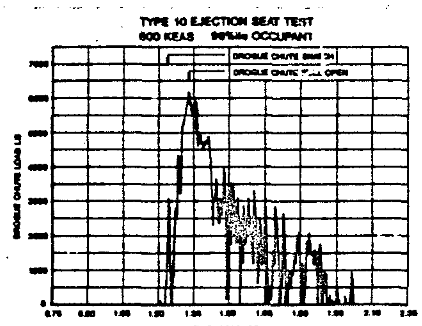
Case No 195.

This case involved an instructor, flying a single seat aircraft in a pairs formation, who went missing in some mountains after a low level abort. The aircraft was found twenty four hours later, the ejection seat three days after the accident, and the pilot's body, four days after the accident. Investigation showed that the pilot had been dragged for some 300-350 metres, over rough ground, before being pulled over a crag. Subsequent reconstruction of the aircraft and ejection seat trajectory showed that the pilot could have been in parachute descent for one, to one and a half minutes, prior to parachute landing. There was no evidence of any post ejection drills being accomplished. The autopsy showed multiple skull fractures, most of which appeared to be post-mortem, but one, behind the right ear, showed evidence of rather more bleeding, and might thus have been ante-mortem. Examination of the ejection seat revealed that the parachute had been extracted laterally with considerable force, to the extent of actually fracturing the parachute container where it was restrained within the ejection seat.

These two cases, which occurred within six months of each other, triggered an investigation into the stability of the particular type of ejection seat concerned. Initial information from the trials films indicated that yaw rates in excess of 2000 degrees $sec.^{-1}$ could occur, but these data had been obtained by a simple single axis analysis of progressive frames of 35mm film. These rates were far in excess of anything that had been measured using angular rate gyros on other similar ejection seats. Since angular rate gyro data were not available for this particular mark of seat, a mathematical solution was derived. This, in conjunction with an ejection seat model and a computer program for the derived instantaneous angular positions of the ejection seat, as seen in progressive film frames, gave results that compared reasonably well with rate gyro data. Reprocessing of the data using the new method revealed peak yaw rates occurring during rocket burn, of between 950-1000 degrees $sec.^{-1}$. These values were consistently obtained across the speed range from 340-600kts. It should be noted that although these figures for yaw rates are high, they have historically been deemed acceptable (Buchanan 1981). The significance of such yaw rates is in the indication of the degree of ejection seat instability, occurring early in the ejection sequence, and the consequential effects that this instability would have on subsequent drogue and parachute deployment vectors.

Drogue Deployment

Loads occur during drogue deployment at so called 'drogue snatch' and at drogue inflation. Drogue snatch occurs at line stretch, and is caused by the mass of the drogue system being suddenly accelerated to the velocity of the seat. On most Martin Baker seats, this is characterised by a sharp peak and a short duration (McDonell Douglas Aircraft Company 1981). A typical example is seen in Figure 1.



DROGUE CHUTE LOAD

FIGURE 1

The snatch load is the first triangular spike of 1362kgf (30001bf) with a 30 millisecond time base. Analysis of data from a variety of ejection seat types and from several manufacturers shows that the acceleration vector with respect to the seat can act in almost any direction (Figure 2).

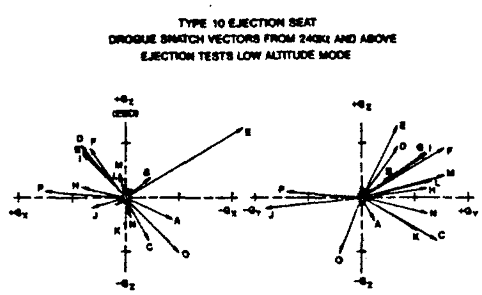


FIGURE 2

Drogue opening

Drogue snatch is followed by drogue opening, and considerable loads can be encountered. Figure 3 is a trace from a test ejection of a new type of parachute headbox, and a -45Gy peak can be seen on an approximately triangular pulse of 140 silliseconds duration.

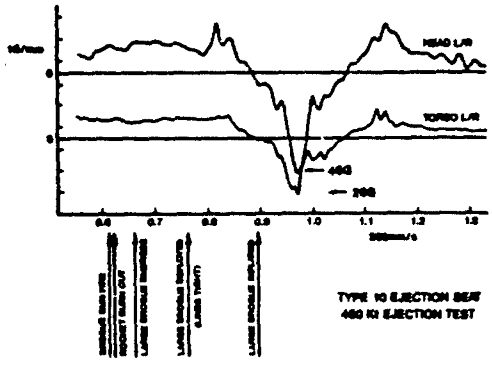


FIGURE 3

Figure 3 also shows that there is a significant difference in the magnitude of the acceleration in the head Left/Right (L/R) trace and the man L/R, as recorded in the torso of the test dummy. Lack of fidelity in dummy neck response makes the evaluation of such data problematic, but it is clear that such accelerations are highly undesirable. Such drogue opening accelerations are not unusually high ven compared with other seat test data. Modern escape systems, however, produce more consistent application of such lcads due to earlier, and more reliable deployment of the drogue. The drogue forces have on occasion been high enough to fracture the shackle stops on the top of the ejection seat and shear away part of the top cross beam assembly.

Parachute Opening Forces

The parachute snatch force is produced at line stretch as the mass of the parachute is accelerated to the velocity of the seat occupant. The orientation of the force vector to the crewman is dependent upon how long the ejection seat has had to align under the drogue, and is thus most random for ejections occurring below barostat height, or below the switch over point for the barometrically controlled G stop on Martin Baker Mk10 seats (Figures 4&5).

TYPE 10 EJECTION SEAT
PARACHUTE SNATCH VECTORS FROM 240Kt AND ABOVE
EJECTION TESTS LOW ALTITUDE MODE

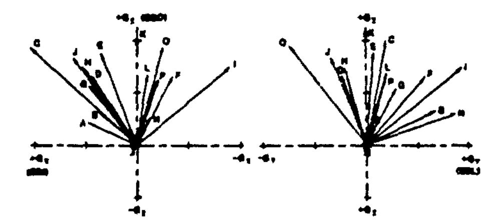


FIGURE 4

TYPE 10 EJECTION SEAT
PARACHUTE OPENING VECTORS FROM 240KT AND ABOVE
EJECTION TESTS LOW ALTITUDE MODE

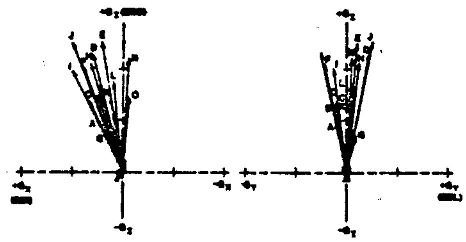


FIGURE 6

Where the scissor schackle release time is extended, seat alignment has time to occur and the deployment vectors are therefore much closer to the ideal, and snatch and opening loads are reduced.

Helmet/parachute riser interactions

Placing the parachute in the headbox of the ejection seat has a number of important benefits. It also has one important drawback in that, for parachute deployments in the vectors forward and/or to the side of the seat occupant, the parachute risers have to sweep around the helmet as the parachute risers go 'lines tight'. One fatal accident has occurred where there was some evidence to indicate that the aircrewman's helmet came into contact with the parachute risers with sufficient force to leave witness marks on both the helmet and the visor assembly. The crewman concerned died of a sub arachnoid haemorrhage but without evidence of any focal injury. Subsequent laboratory experiments, conducted at forces well below those encountered on escape, demonstrated the capacity for the parachute risers to interact with protrusions on the helmet when the risers deployed on vectors in the forward hemisphere of the ejection seat. This qualitative experiment demonstrated not only the importance of helmets having smooth external profiles, but also the need to ensure that ejections are as stable as possible so that acceptable parachute deployment vectors can be achieved.

The combination of test evidence from previous marks of seats, together with concern over the number of fatal, but otherwise within envelope ejections, generated the requirement that any new mark of ejection seat must be stable. Accordingly the United Kingdom raised a specification requiring a new ejection seat to be maintained in a stable attitude in the X, Y and Z axes from ejection initiation up to man seat separation. In a forward facing ejection, the seat was required to remain face into wind in pitch and yaw within +/-20 degrees. Additionally, the angular motion of the occupants head (type of dummy not specified) was required not to exceed 30rad sec.$^{-1}$ angular velocity or 4500 rad sec.$^{-2}$ angular acceleration.
As a further measure, following the period of stabilised flight on the drogue, and for parachute canopy container opening at speeds in excess of 150 KEAS, the angular displacement of the dummy torso relative to the centreline of the deploying parachute was required to be controlled within the limits of pitch defined by MIL-S-18471G, and within 15 degrees in roll and yaw. These angular limits are to be maintained throughout the time interval between recovery parachute lines stretch and recovery parachute first full open.

Head/Headbox interactions

Windblast, and off axis drogue and parachute forces can result in the head being brought forcibly into contact with the ejection seat headbox. This first became of serious concern during the high speed ejection testing of the Mk10A ejection seat used in the Tornado. Analysis of the high speed cine film from a 628kt test ejection showed that, during the initial rise of the seat, the inertial reaction to the +Gz acceleration forced the dummy's head forward onto its chest. As the head and the top of the seat emerged into the air flow, the head was driven forcibly back into the front of the headbox. Substantial damage was caused to the helmet. Subsequent calculation, based on the aerodynamic loading, indicated a maximum impact velocity of 13.6m.sec^{-1}, (Glaister & Gilbert 1975). Assuming a slightly lower impact velocity of 12m.sec^{-1} and a 6.8kg combined head helmet mass, gives an energy of impact of approximately 460 Joules, rather more than twice the 200 joules design criterion laid down in the then British Standard 2495:1960. As a consequence of this incident the ejection seat headbox of the Mk10A seat was modified to improve its impact attenuation. Following modification, the headbox/helmet successfully attenuated impacts energies up to 570 Joules without exceeding 20 kN transmitted force, or a peak acceleration of 310G. Regrettably, the principle of specifying headbox attenuation was not carried over to other ejection seats, and operational experience began to accrue indicating that helmet/headbox impacts, however occasioned, were a cause of impairment of consciousness on escape. Two cases serve as examples:

Case No 108 (Anton op cit)

This pilot was taking part in spinning trials on a new two seat aircraft. Following failure to recover from a spin, both pilots ejected, the subject pilot from the rear. On subsequent examination of this pilot's flying helmet there was evidence of contact between the helmet and one wing of the ejection seat headbox. Following the accident the pilot showed a residual retrograde amnesia of about one minute, and a post traumatic amnesia of approximately thirty minutes.

Case 4/83 (Anton 1983)

This groundcrewman was flying in the rear seat of an aircraft that struck some high tension wires. Shortly after the impact the man ejected. Examination of his helmet and the ejection seat headbox revealed that there were two areas of damage at the rear of the helmet where the helmet and headbox had come into contact, with transfer of material between the two. The crewman suffered a period of post traumatic amnesia of at least five minutes duration which may have included a period of frank unconsciousness.

A further accident occurred in which an aircrewman ejected and was subsequently observed, apparently unconscious, beneath his parachute, for some ten to fifteen thousand feet, before entering and being lost at sea. The Board of Inquiry considered head/headbox contact as one of the possible causes of loss of consciousness and requested that an investigation be conducted into the impact attenuation of the ejection seat headbox then fitted to RAF Hawk aircraft. This investigation (Gilks & Anton 1987) demonstrated that the export headbox had approximately twice the impact attenuation of the version then fitted to RAF aircraft. Much of the improvement in attenuation actually stemmed from the differing constructions employed, it being considerably easier to distort the export headbox than the RAF one, ie. the attenuation of the export box was a function of the construction, not of the impact attenuating material placed on the front of it. This observation was of some significance since there was an emerging requirement to make headboxes significantly less intrusive, so as to improve pilot head mobility in combat. One of the methods adopted to meet this requirement was to pack the parachute at higher packing pressures, a method that resulted in a significant increase in stiffness and thus diminution of inherent impact protection.

McKenzie (1987), reviewed helmet usage amongst aircrew ejecting from RAF fast jets. This review, which was incomplete because not all helmets were available for inspection, showed that seventeen out of two hundred and twenty three aircrew ejecting successfully suffered helmet impacts. Sixteen of these helmets were available for inspection, and the cause of the impact damage was described as ejection seat, usually headbox, in seven cases.

The requirement to move the front face of the ejection seat headbox further aft in order to improve pilot head mobility has two important effects. Firstly it reduces the space available for the parachute, thus probably raising the stiffness of the parachute container for the reasons already indicated; and secondly it increases the distance available for the head to accelerate over, and thus the impact velocity, in the event of a head/headbox interaction. A third problem is also forseen. The introduction of helmet mounted equipment requires the careful distribution of component items around the helmet in order to maintain acceptable weight distributions. It is likely that some of the space available in the occipital area of the helmet, currently used for impact protection, will be occupied by equipment sub-assemblies, thus reducing the level of impact protection afforded by the helmet. It was therefore decided to frame the requirement for headbox impact protection in terms that took account of the protection provided by the actual helmet adopted.

The UK submission for the specification therefore reads:
'The front face of the seat headrest shall be designed such that the combined attenuation of the helmet and headrest shall limit peak head accelerations to 250G for impact velocities up to $14 m.sec^{-1}$'. To enable development work to proceed the specification continued: 'The impact attenuation of the helmet shall be taken as being capable of limiting the peak deceleration to 300G for an impact energy of 122 joules with an equivalent head and helmet mass of 5.7kg'.

Summary

This paper describes an evaluation of the problems of ejection seat instability, and the aetiology of head injury, in Royal Air Force ejection experience since 1968.

Part of the resulting UK input to the specification for a new ejection seat for the European Fighter Aircraft has been described. The new features are principally related to improvements in ejection seat stability and parachute head box impact attenuation.

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ESCAPE SYSTEMS RESEARCH AT RAE

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SUMMARY

A range of recent topics in the escape systems research programme at the Establishment is described. Prominent among these is the computer simulation of ejection seat dynamics which enables prediction of the behaviour of escape systems in different conditions, and complements the experimental methods of investigation. Other topics described include passive methods of seat stabilisation using plates to supplement a bridle-mounted drogue, use of a reefed drogue to improve deceleration characteristics, consideration of some novel methods of deceleration, and use of inflatable restraint devices. Electronic sequencer developments are described, leading to provision of a high capacity, high reliability sequencer for trials use. The paper concludes with a consideration of biodynamic modelling and dummy development.

INTRODUCTION

The work of the Royal Aerospace Establishment at Farnborough UK includes research and development on aircraft escape systems. In this field, we work closely with industry (Martin-Baker) and the user (represented typically by the RAF Institute of Aviation Medicine). One of the key elements in the RAE programme of research is the computer simulation of ejection seat dynamics.

COMPUTER SIMULATION

This is a six degree of freedom simulation, which can be used to predict the trajectory and attitude of an ejected package under a wide range of different conditions (ref 1, 2). The equations of motion describe rigid body freedoms of the ejected package in the three linear and three angular directions. The package consists of the seat and occupant when first ejected, acted upon by the forces and moments generated by propulsive loads, aerodynamic loads, parachute loads, etc (fig 1). When the man separates from the seat, the model changes to a two body simulation which consists of man and parachute canopy joined by the parachute rigging lines (fig 2). Numerical integration of the equations of motion produces a time history of the motion for all axes, and all phases of the ejection can be simulated from initiation of ejection to arrival on the ground.

The greatest uncertainty in the predictions made arises from the limitations of the aerodynamic data. A comprehensive set of static aerodynamic coefficients was obtained experimentally from tests of one-third scale seats and dummies in a transonic wind tunnel at ARA Bedford, and this was backed up by limited full scale tests in a 24 ft wind tunnel. These data are incorporated in the computer model as a matrix of data points which are interpolated by the program. In practice, aerodynamic moments are sensitive to small changes in the proportions of the seat occupant and changes in his posture, so that for an unstabilised seat, an accurate time history of the motion is not readily predicted when the airspeed is significant. However, under low air speed conditions and for a stabilised seat under any conditions, a good match is possible between prediction and reality. At all speeds, the simulation is an excellent means of predicting trends in behaviour arising from systems modifications or new design features. The simulation is also readily adaptable for use in dynamic applications other than ejection seats.

Of course, the simulation complements the use of experimental methods in the research programme. The main test facilities in use are rocket sleds at Pendine in South Wales (fig 3), and the ejection tower at Farnborough (fig 4). For escape parachute testing, air-dropped parachute test vehicles (ref 3) and a compressed air launcher (ref 4) are available. Use is also made of wind tunnels when required. Comprehensive instrumentation facilities are used to extract the maximum data from expensive and time-consuming trials. The simulation is regularly validated against trials data to ensure that it gives realistic behaviour.

The simulation is used to assist the escape community in a wide range of tasks, including accident investigation for RAF IAM, but its main application is as a research tool. It is used to assess and optimise many prospective improvements to escape systems which arise from the escape technologies being developed at the Establishment, as will be described in the following paragraphs.

SEAT STABILISATION

Ejection seats are not renowned for their aerodynamic stability in a high speed airflow. Without special precautions, a free-flying seat can rotate in the airflow and cause parachute shock loads to be applied to the aircrewman in hazardous directions (fig 5). Our aeromedical colleagues at RAF IAM have highlighted this problem, and it is well recognised that lateral loads of more than 15 g applied to the head-neck system carry a high risk of injury (fig 6).

To overcome this problem, passive means of stabilising an ejection seat aerodynamically have been developed at RAE (ref 5, 6). The primary technique is to attach the drogue by means of a three-strop bridle, so that the seat is held upright and facing into the airflow (fig 7). The drogue needs to be deployed early, but this risks interference with the fin of the aircraft. Therefore to provide early yaw control, aerodynamic plates should be added to the seat. Fig 8 shows experimental plates mounted on one of the one-third scale model seats already described, to determine their effect in the wind tunnel. Fig 9 shows plates of proven design installed on a full size seat which have successfully controlled the yaw attitude in ejection trials (ref 6). In service, the plates would need to be folded while the seat is in the cockpit and then deployed on ejection. Fig 10 shows the improved stability and reduced lateral g which result.

DECELERATION CONTROL

One of the problems with using the drogue as a stabilising device is the need to deploy it early in the sequence, when airspeed may be high. To avoid excessive deceleration loads on the man, the size of the drogue must be reduced. But then apart from the limited authority which a small drogue will have, as the speed decays the drogue will become less effective in slowing the man. Thus it will take longer to reach a safe condition for main parachute deployment and the margin for safe escape will be reduced.

A typical deceleration trace for a simple drogue is shown in fig 11. A noticeable feature is the large dip in the trace in between the drogue inflation and the main parachute inflation. Therefore we require a drogue parachute with a variable canopy area. Such a system has been developed under contract at Irvin GB and refined by RAE. Deceleration peaks are reduced by allowing the drogue to open progressively in stages under micro-processor control as the velocity decays.

Fig 12 shows how the opening of the drogue is controlled. The peripheral reefing line is arranged in a clover-leaf pattern and joined to a centre line which is released in stages by pyrotechnic actuators. Fig 13 shows the release block built in to the confluence point of the rigging lines and containing a number of redundant actuators. These enable three stages of de-reefing to be achieved reliably. Ejection trials of the system have highlighted some problems with initial inflation of the drogue but these are being addressed (ref 6).

Fig 14 shows the result of applying the system. It is evident that much of the dip in the deceleration trace has been removed so that the man is decelerated more consistently and more rapidly.

Of course when used in a lower airspeed ejection the system would be arranged to deploy the drogue in a more fully open state, while below a particular threshold speed the drogue is unnecessary and it would be dispensed with, allowing the main chute to be deployed directly for best performance.

While on the subject of deceleration control, a potential problem arises with the current specification of lightweight seats for aircraft such as EFA. In a 600 knot ejection the initial drag of the seat and man alone, without any parachute, is likely to exceed the critical level of 25 g. Possible ways of alleviating these loads would be to reduce the seat drag with a stream-lined fairing, or to provide a forward rocket thrust to offset the drag. Alternatively, aero-medical opinion may come to accept the extra hazard of the increased g level in view of its short duration and hopefully the rare occurrence of ejections at this speed.

NOVEL METHODS OF DECELERATION

The ideal deceleration trace would have a constant level at the physiological limit of 20 or 25 g, as shown in fig 15. Since much of this deceleration is produced by the drag of the seat and man, and the latter decays as the velocity decays, the contribution from the parachute is required to be low at high speed and high at low speed. This is contrary to the usual rules of aerodynamics, and Industry was invited to study speculative methods of achieving the required result. Studies at Cambridge Consultants (ref 7) and GQ Parachutes (ref 8) considered a number of ideas, the following being among the more interesting.

One approach is to treat the parachute as an anchor in the sky and reel out the line connecting it to the seat in a controlled way. This can be done by using a material such as ply-tear webbing, or by running the line round a controlled capstan (fig 16) or through a friction brake. Up to 20 m of line would be reeled out in this way. Ply-tear webbing gives a fairly constant force but this is not quite what is required. The simplest of any of these systems is estimated to weigh at least 4 kg and the addition of refinements including a control system would increase this figure substantially.

Another method is to deply a drag body or bodies mounted on the seat itself. This could take the form of an array of hinged plates, or an inflatable structure (fig 17), arranged shuttlecock fashion. At increased speeds, the drag surfaces would tend to align themselves with the flow and reduce their drag coefficient. Unfortunately the result falls short of the desired effect unless a complex control and actuation system is added. Studies suggest that the drag plates may be worthy of further investigation, but an inflatable structure of this type would be excessively heavy in respect of weight of fabric and weight of gas.

The overall conclusion of these studies was that it would be difficult to improve on the reefed drogue system already being developed.

INFLATABLE RESTRAINTS

At the same time as inflatable structures were being studied for use as drag bodies, their use for restraint devices was investigated. A contract at Cambridge Consultants has produced the prototype inflatable head restraint shown in fig 18. The device is stowed on the headbox in normal flight and would be inflated on ejection. This prototype is being used in laboratory tests to establish techniques for fast and controlled inflation.

SEQUENCE CONTROL

Previous paragraphs referred to microprocessor control of various parts of the parachute system. The philosphy followed at RAE has been to provide such control continuously during the escape sequence and not just in the selection of a mode in the early part of the ejection. Such control requires the continuous input of data from airspeed, altitude and deceleration sensors mounted on the seat.

For measurement of airspeed, a particular design of shielded pitot has been developed (fig 19 and ref 9). Wind tunnel tests show that the output is accurate at airflow angles up to 60 degrees off axis (fig 20). Pressure altitude is measured using an open-ended tube mounted behind the seat where it is well shielded from direct flow impingement from all directions. The reading obtained is a value of base pressure which is somewhat below the ambient static value. Processing of the base pressure and pitot pressure values must be carried out to deduce a value for static pressure. In addition to airspeed measurement, deceleration is measured by accelerometers in each of the three seat axes.

To make use of all this data, intelligent processors are being developed at RAE. Fig 21 shows a prototype microprocessor-based sequencing system which has been developed and which has provided reliable control of the sequence in ejection seat trials (ref 6). This experience led to a specification (ref 10) for a high reliability sequencer with expansion capacity to handle advanced features such as vertical seeking and thrust vector control. Such an experimental sequencer is required on trials seats to conduct research on advanced systems of that type.

A development contract at GEC Avionics has resulted in delivery of three sequencers for this purpose (fig 22). Reliability is achieved by the use of triplex 80C88 processors with majority voting, and further high integrity architecture based on duplicated power supplies and transducers. Input channels include 6 integral accelerometers, 4 pressure transducers, 8 external event switches, and a triplicated synchronous serial data input channel. The serial channel will allow receipt of aircraft data, and/or data from a 3-axis ground proximity sensing system. Output channels include 12 duplexed firing circuits and 6 analogue outputs. Each firing circuit generates a short duration high power current pulse for operating electrically initiated explosive devices. The analogue outputs could provide signals to a rocket vectoring system or a gas jet control system. Non-volatile memory of 2 K capacity enables storage and recovery of ejection parameters.

The flexibility of control provided by electronics allows other control features to be included, such as modulation of the sequence according to the imminence of ground impact. In ejections near the ground, decelerations may be taken to the physiological limit to maximise survival chances. In elevated altitude ejections where the danger of ground impact is remote, a milder level of deceleration can be permitted to reduce the loads on the seat occupant. A less stressful ride improves the chances of a safe recovery. Proximity to the ground can be estimated crudely on the basis of pressure altitude, but it is more accurate and more useful to sense the ground directly with a simple radio-altimeter.

BIODYNAMIC MODELLING AND DUMMY DEVELOPMENT

There is well-publicised concern about the increasing mass of helmet-mounted equipment and its effect on head and neck loadings. At the same time, the dummies available for ejection testing are perceived to have shortcomings in respect of inadequate bending flexibility of the spine and neck, and inadequate compressive flexibility of the spine. Compression of the spine is believed to be a significant factor in the human response to ejection, causing slackening of the harness which encourages slumping of the torso. Similarly, there is evidence that bending of the thoracic region of the spine contributes significantly to ejection response.

Therefore a method of constructing the dummy spine has been devised which provides both bending and compressive flexibility. Fig 23 shows the principle, for which a patent application has been submitted. The spine is based on a nylon bar which provides the appropriate bending flexibility. A series of nylon cotton-reels are a close sliding fit on the bar. Each pair of dummy ribs is mounted on a cotton-reel and the space between adjacent cotton-reels is filled with a rubber washer to provide compressive flexibility. The upper end of the nylon bar is fixed to the shoulder unit of the dummy. At the lower end, the bar is a sliding fit in the dummy pelvis. Representative head dynamics are achieved by careful attention to mass properties of the head and by a new flexible segmented neck. Ejection tower tests of this assembly have demonstrated realistic degrees of slumping of the dummy, and free flight ejection tests at high speed have established the durability of the design. The nylon bar can evidently bend through a considerable angle without suffering any apparent damage.

In parallel with the development of dummy hardware, attempts have been made to model mathematically the human response to ejection. The spine and neck have been represented by a series of lumped masses joined by elastic and viscous elements. Fig 24 shows a sample response to a vertical impulse for one such model. The need for a non-linear response in the model was recognised at an early stage. The eventual aim is to develop a representative model of human response which can be added to the simulation of ejection seat dynamics to improve the realism of the predicted motion.

CONCLUSIONS

It should be clear from the foregoing that escape systems research at RAE covers a wide range of topics. The computer simulation of ejection seat dynamics is a vital tool providing assistance in all areas of this research, and complementing the experimental methods used in trials.

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10	RAE	Specification for a Microprocessor Based Sequencer/Controller for Advanced Ejection Seats Spec No FSF4/ES/84/4 Issue 2, 1985.

ACKNOWLEDGEMENTS

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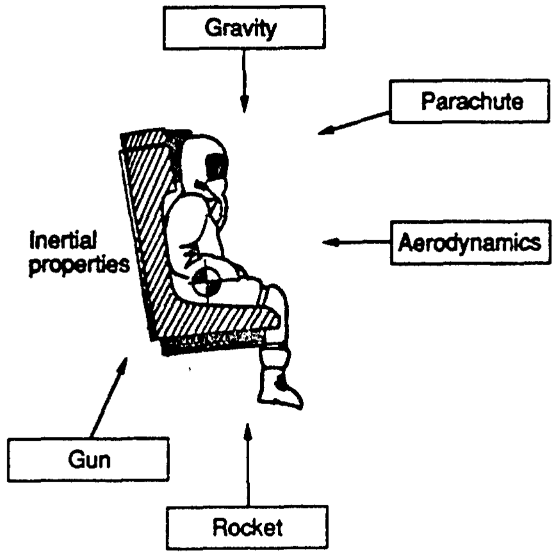

Fig 1 Sources of loading on the ejection seat and occupant

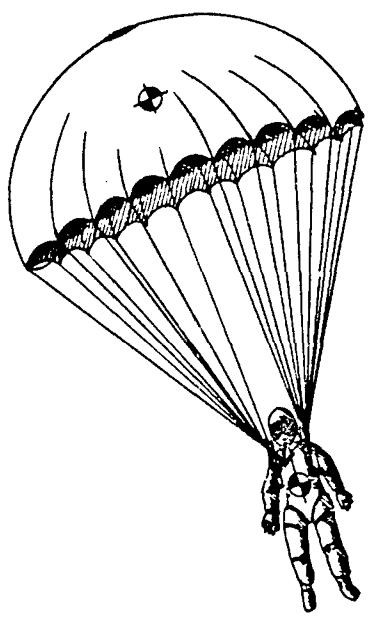

Fig 2 Two body model of man and parachute

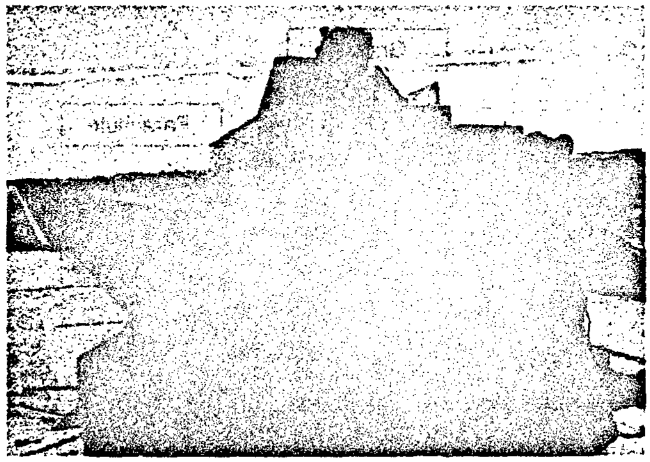

Fig 3 Rocket sled on P&EE Pendine track

Fig 4 Ejection seat test rig at Pyestock

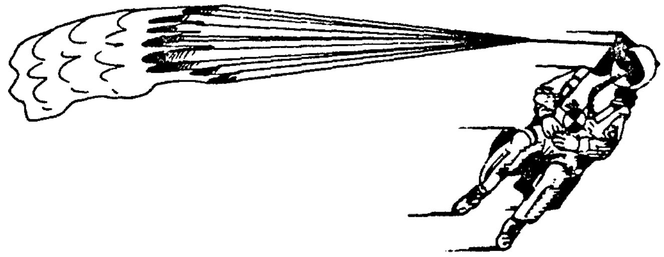

Fig 5 Lateral loading of occupant in an unstabilised seat

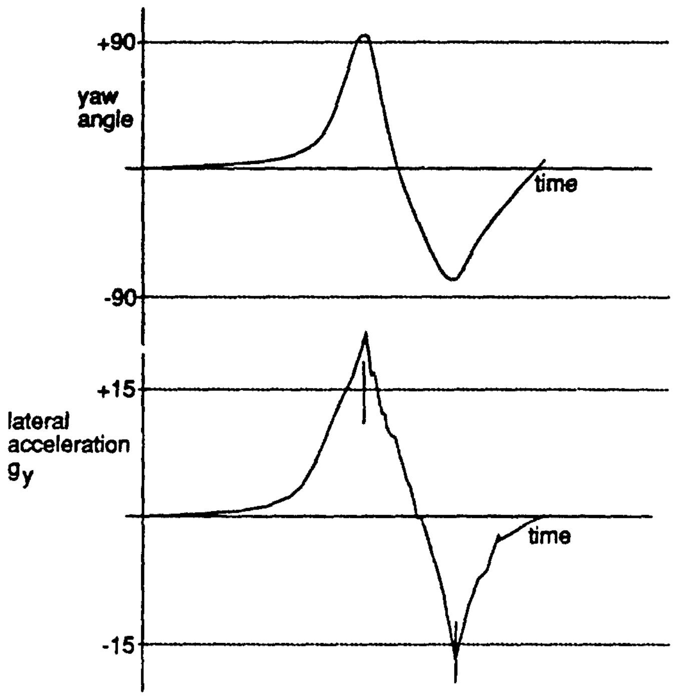

Fig 6 Yaw angle and lateral g for an unstabilised seat

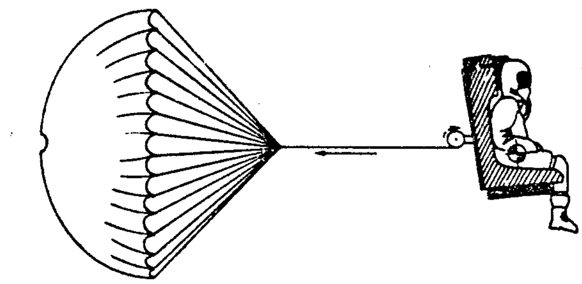

Fig 7 Passive stabilisation by bridle mounting of drogue

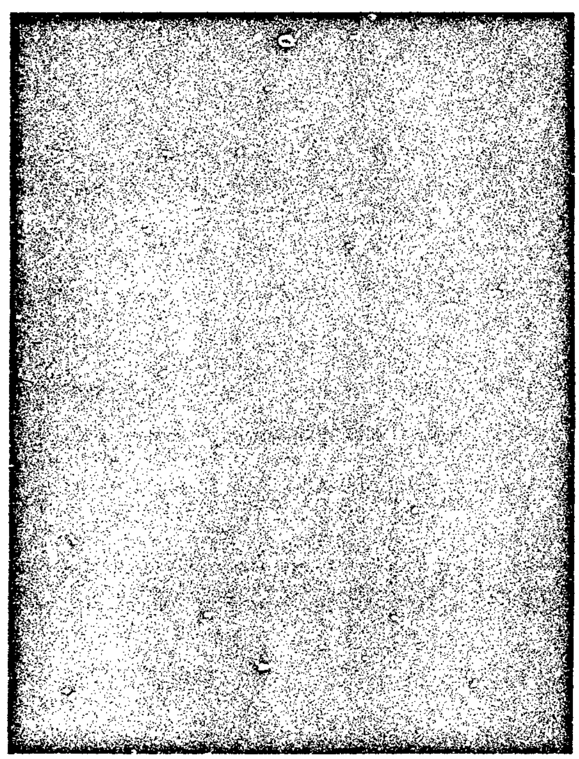

Fig 8 Stabilising plates on 1/3 scale wind tunnel model

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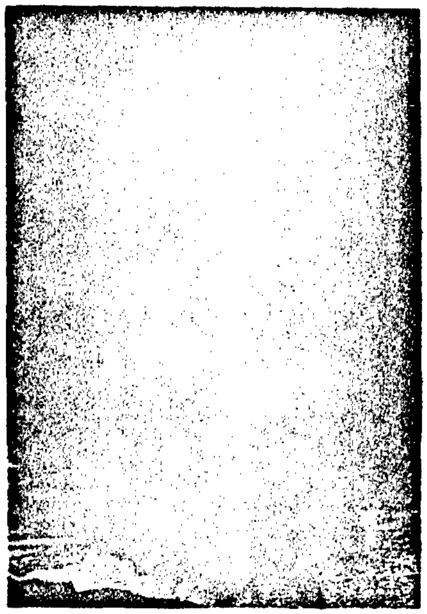

Fig 9 Stabilising plates on a full scale trials seat

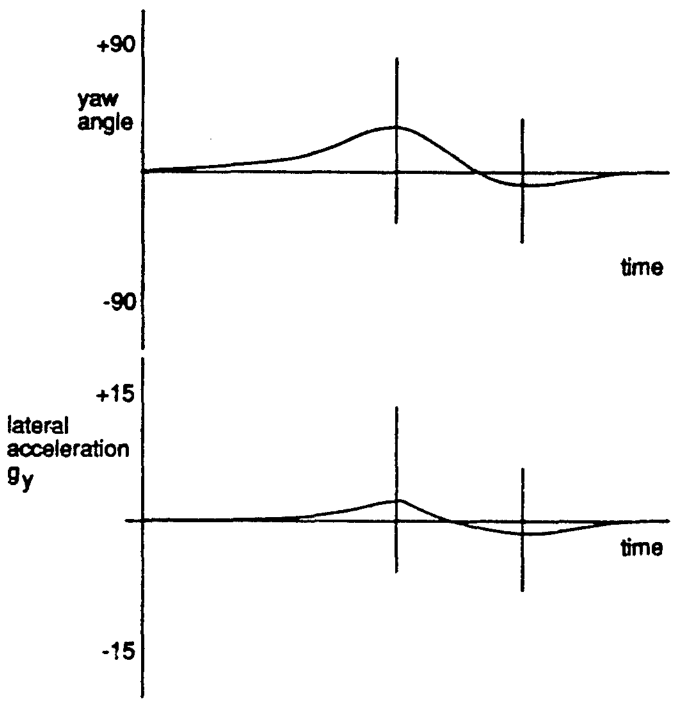

Fig 10 Yaw angle and lateral g for a stabilised seat

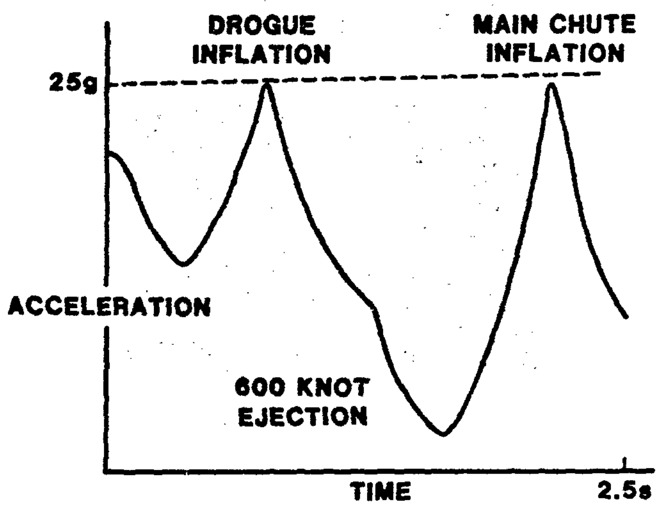

Fig 11 Deceleration trace for a simple drogue/main parachute system

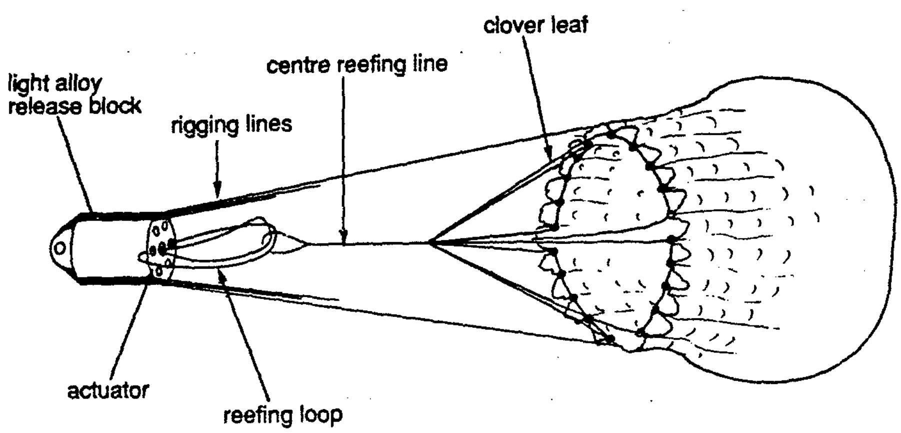

Fig 12 Drogue reefing system

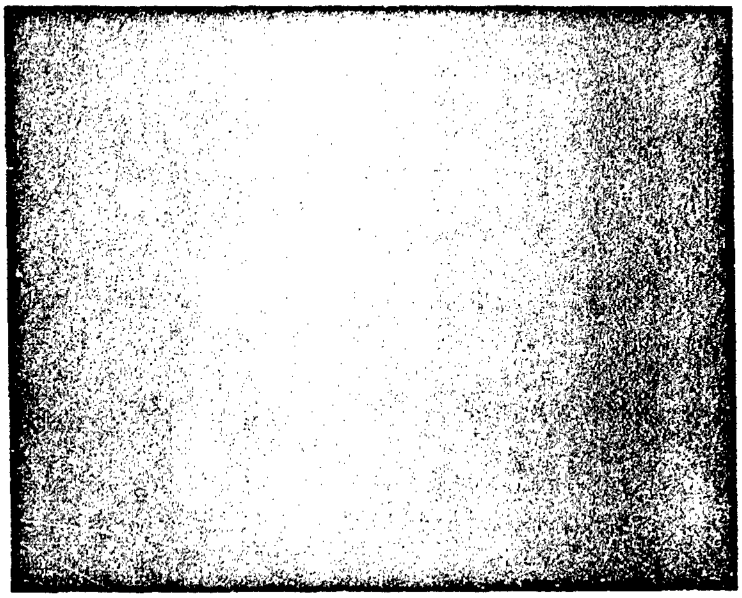

Fig 13 Release block for drogue reefing system

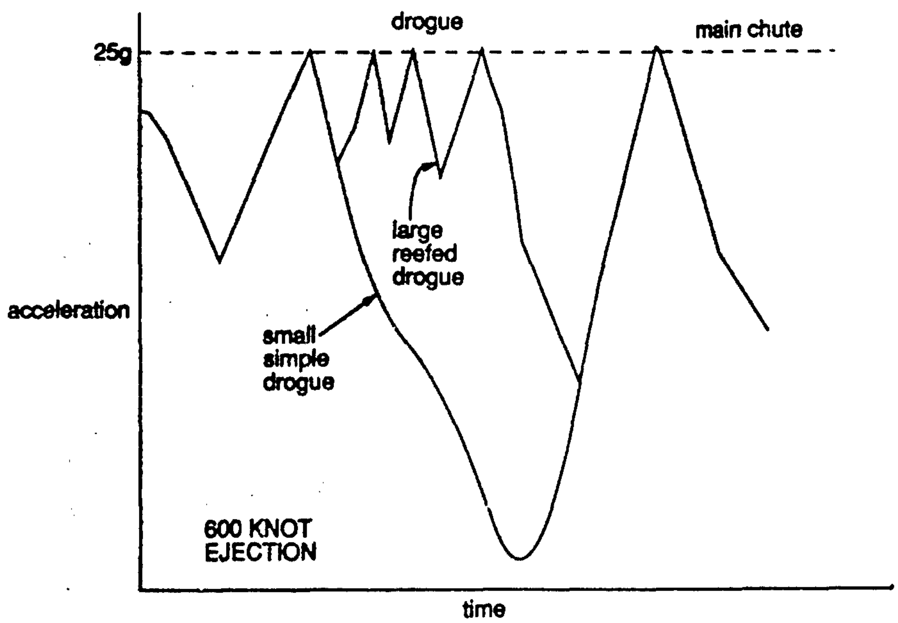

Fig 14 Deceleration trace for reefed drogue system

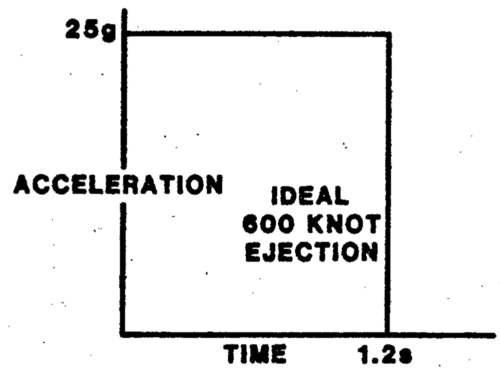

Fig 15 Ideal deceleration trace

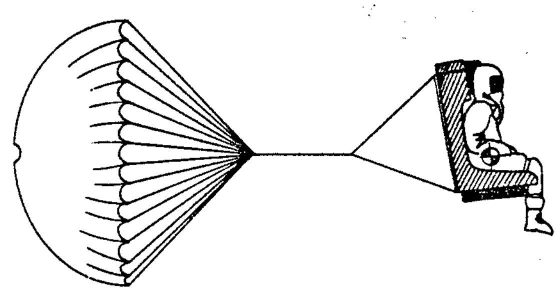

Fig 16 Rope brake system for constant drag deceleration

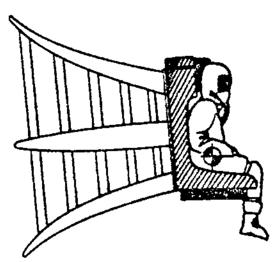

Fig 17 Inflatable after-body
for constant drag deceleration

Fig 18 Experimental inflatable head restraint

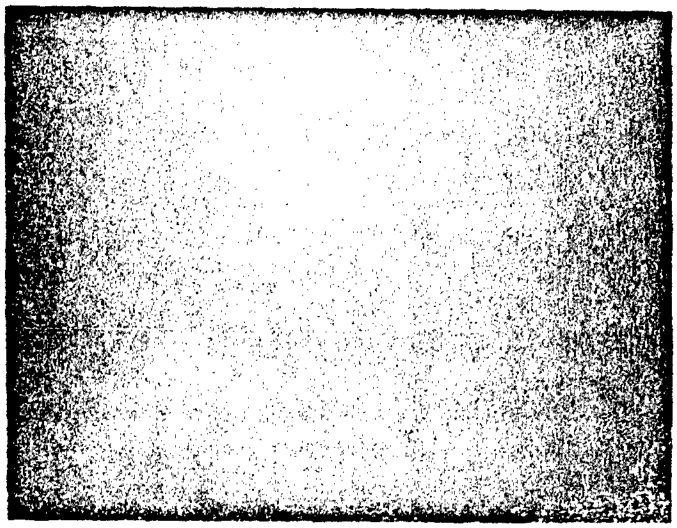

Fig 19 Shielded pitot for airspeed measurement

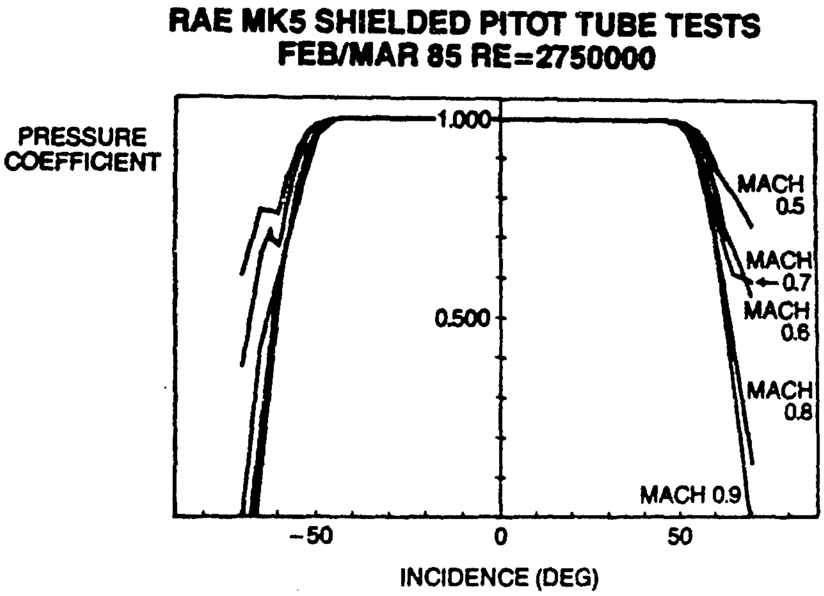

Fig 20 Off-axis response of shielded pitot

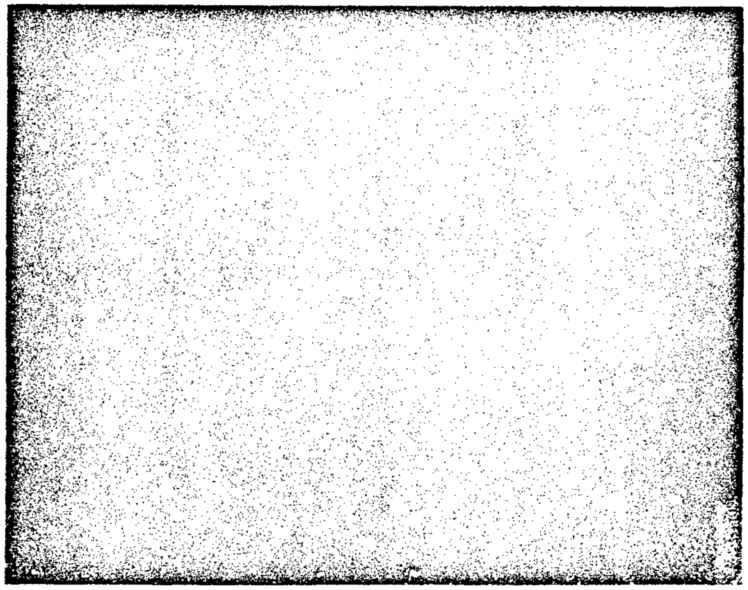

Fig 21 Prototype microprocessor-based sequencer

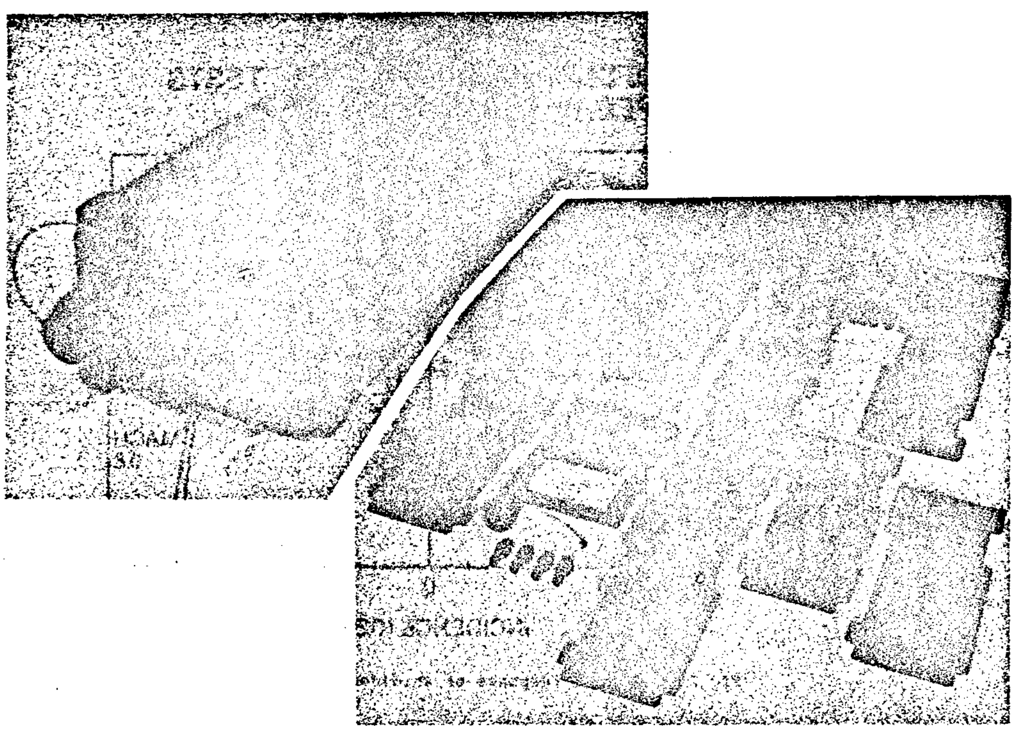

Fig 22 High capacity, high reliability sequencer for advanced ejection seats

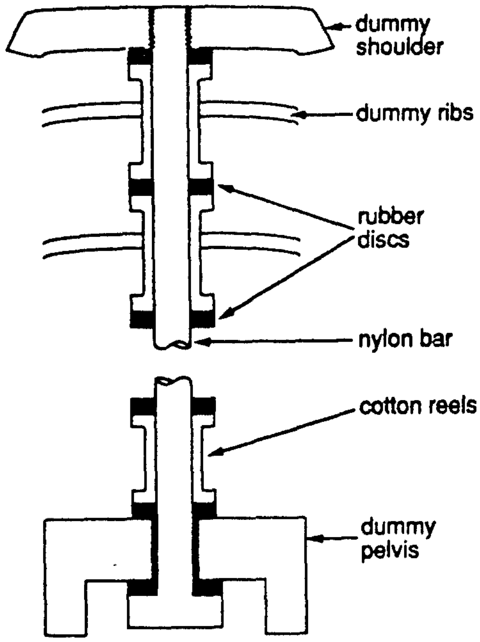

Fig 23 Flexible spine for ejection test dummy

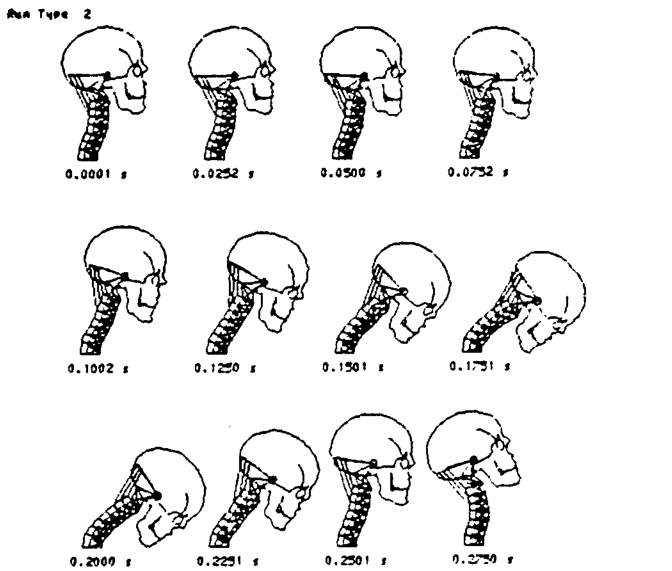

Fig 24 Sample head/neck response of biodynamic mathematical model

FIGHTER ESCAPE SYSTEMS
The Next Step Forward

by

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INTRODUCTION

Ejection seats have become increasingly complex, heavier and bulkier in recent years. This growth has been in response to the increasing demands for greater performance, under more severe conditions. It is also due to the relocation onto the seat of equipment which was previously aircraft mounted such as anti-g valve, oxygen regulator, NBC equipment and OBOGS auxiliary oxygen equipment. In the Tornado, the Mk10A ejection seat even gained outlets for the cabin conditioning system, becoming the worlds first air conditioned ejection seat! This trend has persisted for some 15 years, but now new design drivers are becoming dominant with an increasing and urgent need for lightweight and low cost.

This paper briefly reviews the Martin-Baker developments of the past 15 years and discusses the new trends which are shaping future Fighter Escape Systems.

MK10 1970'S

Martin-Baker design philosophy has always been one of analysing their previous products, retaining the best features and developing improved features to meet new specification requirements. The 5,800 successful Martin-Baker emergency ejections prove the effectiveness of the basic design concept. Tornado, Hawk and Alpha Jet demanded a lighter, quicker acting ejection seat but development of the Mk7 or Mk9 ejection seats would have meant unacceptable weight increases and their back mounted parachutes did not lend themselves to still quicker operation. The traditional Martin-Baker features were therefore repackaged, relocating the new 5.2 metre GQ Aeroconical parachute to a headrest mounted container and providing ballistic operating systems in place of the earlier mechanical systems.

The Mk10 ejection seat dramatically improved seat performance enabling safe ejection to take place under conditions which would previously have been impossible.

Early market requirements for further weight and cost reductions resulted in the development of the Mk10L (lightweight) version which reduced seat weight by as much as 20%. Acquisition costs were also reduced by the use of computer aided manufacturing techniques.

Both the Mk10 and Mk10L ejection seats have proved most successful and are now installed in 35 aircraft types. Their safety record is also impressive with 95% of emergency ejections being successful. It should be noted that the fatalities include all causes, including drowning and out-of-envelope.

TRAINER AIRCRAFT ESCAPE SYSTEMS

In 1977 a new market for ejection seats opened with the Turbo Prop trainer market. In that year, Guido Pessotti, the Technical Director of Embraer in Brazil, began the design study for his then new EMB 312 turbo prop trainer. He did not accept preconceived ideas, but decided to investigate a possible need for ejection seats.

World War II experience had revealed the effect which speed has on recovery rates. Even moderate speed delayed escape too long for safe pilot recovery. At only 200 knots, chances of saving aircrew was reduced to 25%. Above 300 knots, pilot recovery was as low as 2%. With the new turbo prop trainer projected to have a Vne of 330 knots, it was obvious that assisted escape could be justified on the grounds of speed alone.

A further study was conducted to determine if ejection seats could be fully justified for turbo prop trainers. Examination of the Jet Provost basic trainer performance envelope confirmed that it was similar to that of the proposed trainer. Performance characteristics of the Jet Provost and Tucano are similar, with an identical stalling speed (65 knots), but 50 knot higher maximum level speed for the Jet Provost.

In the period under review, there were 107 ejections, of which 102 were successful, giving a recovery rate of 95.3%. In all unsuccessful cases, ejection was initiated well outside the performance envelope of the ejection seat. Only six of the 107 ejections had a reported ejection speed in excess of 300 knots. The vast majority (91.1%) of ejections, where speed was reported, occurred within the level speed range of a turbo prop trainer, 75% were between 75 and 150 knots. Thirty-nine ejections took place below 1,500 feet.

The study came to the following conclusions:

1. The 107 ejections which took place from the Jet Provost during the subject period, could have taken place from a turbo prop trainer. The accident rate and

circumstances were to be expected with any future medium performance basic trainer operating in similar conditions.

2. Over 30 pilots who successfully ejected below 1,000 feet would, almost certainly, have been lost had ejection seats not been fitted.

3. Safe escape under conditions of loss of control below 4,000 feet or fire in flight, would be marginal without ejection seats.

4. An unknown, but most significant, number of safe landings have been made in Jet Provost aircraft following an in-flight emergency which would have necessitated early abandonment had ejection seats not been installed. Because escape could be safely delayed, the pilot had the option of conducting an approach to a safe landing. In some engine failure cases, the glide could not be extended sufficiently and the pilot ejected successfully at an altitude at which safe abandonment would have been impossible.

For Tucano, the Mk10L ejection seat was modified by removing the rocket to save weight, thereby giving a performance of 60 knots on the runway. All Tucano customers opted for ejection seats and the Tucano has proved to be an outstanding success story.

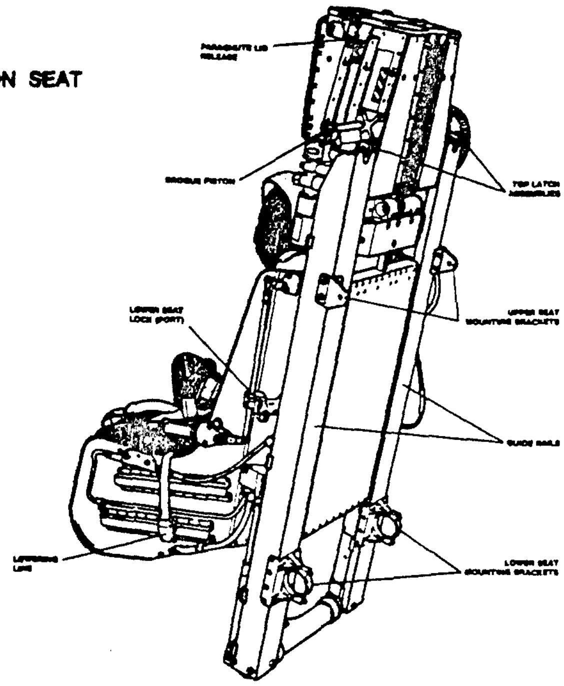
Mk11

Not be to outdone, Pilatus in Switzerland, produced the PC-9 equipped with ejection seats from the outset. This time a lighter, specialist seat was developed by Martin-Baker, this being the MkCH11A. This seat employed the traditional MBA design layout, but was more compact and lighter than the Mk8L seat developed earlier for the Tucano.

Mk15

With the ejection seat equipped basic trainer firmly established, operators of similar performance aircraft, such as the PC-7, began to press for ejection seats. Because the PC-7 cockpit was designed for over-the-side bale-out, there was no possibility of installing the Mk11 seat, there being insufficient fore and aft space available. Martin-Baker set to work with Pilatus to develop an entirely new seat which would occupy the same position as the existing fixed seat and parachute. After extensive innovative design work, this goal was achieved by positioning the pilot between twin ejection gun tubes close to the cockpit rear bulkhead. The twin ejection guns also act as the seat primary structure. In this way the correct sitting position and eye datum points were retained.

MK15 EJECTION SEAT



In order to minimise the effect on aircraft performance by the installation of ejection seats, it was essential that weight be kept to a minimum. This was achieved by employing components for multiple functions so that, for example, the ejection gun and guide rails form the primary seat structure to withstand flight and crash loads. The result has been the development of the worlds lightest and smallest production ejection seat, weighing only some 78 lbs (35 kg). Thus the light trainer market generated the light seat concept because minimum mass was a major design driver.

HIGH TECHNOLOGY DEVELOPMENTS

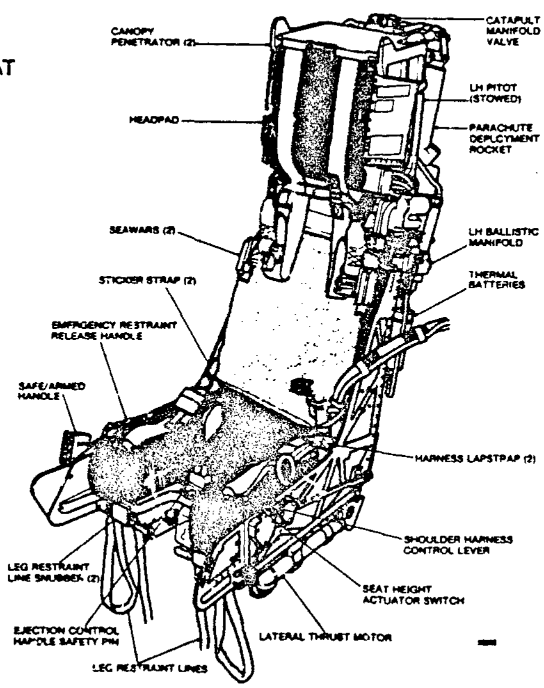
Meanwhile, in parallel with the search for ever lighter weight ejection seats for the trainer aircraft field, the high performance aircraft field continued to demand greater performance. This resulted in the Mk12 series ejection seat with Mechanical Speed Sensing and Sequencing and this in turn led to the Mk14 with Electronic Sequencer control.

The Mk14 was developed specifically for the United States Navy Aircrew Common Ejection Seat (NACES) programme and incorporates state of the art technology. When reviewing the specification requirements issued by the Navy in 1984, the following design drivers emerged:

* Minimum Programme Schedule Risk
* Common seat for four aircraft types with no airframe changes
* Electronic sequencer operation
* High performance and serviceability
* OBOGS compatibility
* Low Life cycle Costs via ILS
* Installed mass of not more than 215 lbs

As the Mk10 ejection seat in the F/A-18 Hornet was already popular with pilots and groundcrews, that basic design was adopted to minimise programme schedule risk. The Mk14 design was selected for NACES and is now being introduced for the F/A-18 Hornet, T-45 Goshawk, F-14D Tomcat and a new combat aircraft in development. Some 80 test ejections from zero-zero to Mach 1.2 at 50,000 feet have proved that the seat has significantly improved recovery capability compared to earlier seats. A new microprocessor controlled electronic sequencer developed by Teledyne in the United States, a greatly improved stabilization system by Irvin (GB) and parachute by GQ Parachutes have been successfully combined in the most advanced ejection seat to enter production. Initial deliveries have commenced and quantity production will be underway later this year.

MK14 NACES
EJECTION SEAT



THE NEXT GENERATION

With NACES, the U.S. Navy took a quantum step forward in escape system technology, advancing the state-of-the-art. Meanwhile, the U.S. Air Force have pursued a different approach with the Crew Escape Technology (CREST) programme, which is developing new enabling technology to extend future ejection seat capability. This work includes variable thrust, steerable rockets, upward seeking systems and other advanced technologies. Martin-Baker, being a non-U.S. company, was not allowed to bid and Boeing succeeded in winning this contract. Although they have encountered major difficulties, Boeing are developing some new technologies which may have significant future applications. Although not intended for production, CREST has shown that these advanced techologies can be costly and heavy with a production ejection seat likely to cost 3-4 times more than NACES and weighing at least twice as much.

MK16 - THE NEXT STEP FORWARD

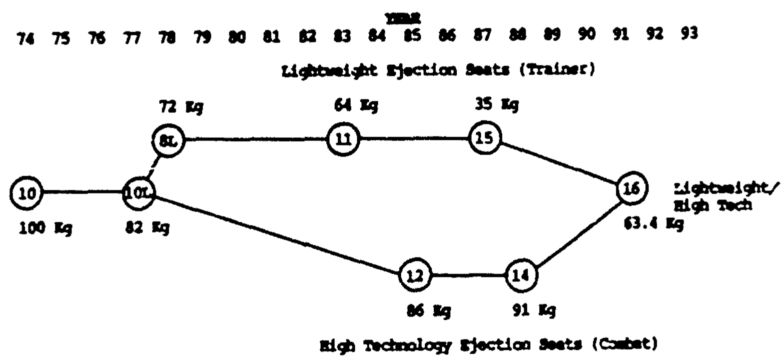
Martin-Baker had hoped to develop a range of NACES derivatives each suited to the particular detailed requirements of future combat aircraft. With relatively minor changes to the harness, survival kit, outer envelope, etc, NACES would very adequately meet the performance requirements of the next generation of fighter aircraft, but our study of requirements revealed that the design drivers had changed yet again. They are now seen as follows:

* Minimum mass
* Minimum cost/L.C.C.
* Improved Pilot efficiency
* High Serviceability/Reliability
* Sophisticated electronics
* Performance to NACES standard

The next generation of European fighter aircraft are to be built to very strict mass and cost limits.

In order to respond to these new design drivers, Martin-Baker have combined the two development paths of the ultralight trainer seat and the high technology, high performance combat aircraft seats to create the Mk16 series. The new design drivers have been addressed as follows:

DEVELOPMENT MILESTONES
(MK10 TO MK16 EJECTION SEAT)



MINIMUM MASS

The multiple function structural features of the 78 lb (35 kg) Mk15 ejection seat have been strengthened and modified to suit the next generation fighter requirements. This results in a Mk16 ejection seat weighing only 139 lb (63.4 kg) a directly comparable weight saving of 30% compared to NACES.

MINIMUM COST

CAD/CAM design and manufacture, simpilicity of design and long installed component lives reduce ownership costs even beyond that already achieved for NACES.

IMPROVED PILOT EFFICIENCY

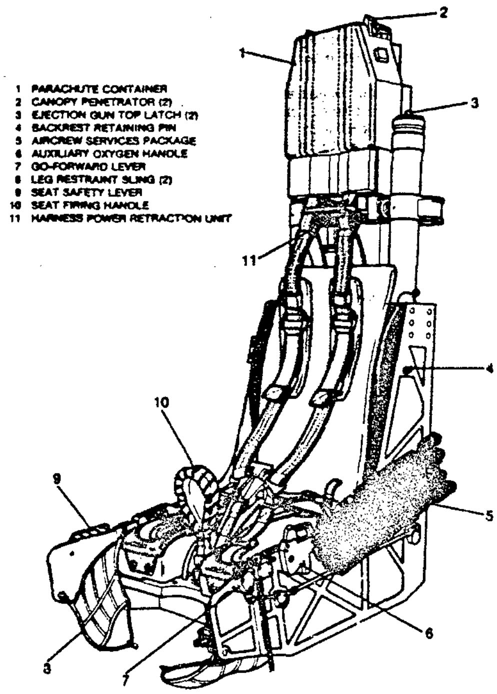
The Mk16 ejection seat is designed for ease of strapping in and emergency egress, together with further improved pilot comfort and support. Pilot field of view has been significantly increased to enable the full advantages of modern bubble canopies to be realised while enabling the full use of helmet mounted systems. The development of ever more cophisticated helmet mounted equipment has also increased the head supported mass, a feature not conducive to safe high g combat or ejection. Although the helmet systems mass will be minimised, there is already a trend to reduce impact protection performance of the helmet in order to reduce head supported mass. This requires that the head impact attenuation properties of the seat headrest be increased to compensate for the reduced helmet protection and this has been achieved without increasing the minimal profile for the headrest. With integral NBC protection, anti-g, oxygen systems and weapons systems, the Mk16 ejection seat will become a major feature of the crewstation and will significantly contribute to the overall efficiency and effectiveness of the pilot.

HIGH SERVICEABILITY/RELIABILITY

The Mk16 will set a new standard for reliability, serviceability and ease of maintenance when required. For example, removal of the seat will now take one man 12 minutes and will not require removal of the aircraft canopy.

SOPHISTICATED ELECTRONICS

A second generation microprocessor controlled electronic sequencer has been developed to control seat operation more accurately and provide greater redundancy. The unit is capable of being integrated with the aircraft databus to upgrade performance by responding to aircraft attitude and pitch, yaw and roll rates at the time of ejection. This would enable the seat to respond to the precise condition at the time of ejection and tailor seat operation rate to the criticality of the emergency. Provision is also made for health monitoring and Built-in-Test. This advanced sequencer also incorporates a Non-Volatile Memory which stores the ejection conditions and acts as an additional accident data recorded. All of this has been incorporated in a smaller envelope than the first generation NACES system, saving on seat size and mass.



MK16 EJECTION SEAT

EJECTION PERFORMANCE

NACES represents an advanced and effective mode of seat operation. Immediately after ejection, the seat is stabilized on a three bridle ribbon drogue which holds the seat upright and facing into wind during rocket burn. At high speed or altitude the drogue is retained until the closed loop sensing system signals its release immediately after the rocket deployment of the main parachute. The Parachute Deployment Rocket fully streams the bagged canopy in under 1 second, and the bag is removed permitting progressive hem-first inflation producing safe canopy opening without high snatch loads. The GQ 6.2 Aeroconical parachute developed for NACES has been increased in diametre to 6.5 metres, while at the same time reducing its packed bulk by 30%. Parachute performance is slightly improved over the fully U.S. qualified GQ 6.2 metre Aeroconical, while the smaller packed volume in the headrest container assists in the improvement of pilot field of view.

NACES operation has been extensively and reliably demonstrated by over 80 tests at NWC China Lake and our own facilities. The adaptation of the NACES operating methods provides outstanding performance backed by extensive trials experience.

By taking the best NACES technology and improving it to meet the even higher standards specified for the European market, a new generation ejection seat has been developed. It meets realistic specifications and safety goals and is several orders of magnitutde lighter and less expensive than other future escape systems currently in development.

WHAT PRICE SAFETY?

In developing the Mk16 ejection seat, we appreciated that some customers would want the lightness, comfort, field of view, method of operation and low speed, low altitude performance of the Mk16, but would be unable to justify the additional costs of a sophisticated electronic sequencer system. We therefore decided to develop a mechanical Mode Selector version in parallel with the electronic seat.

It has been possible to mechanically "duplicate" the electronic system, giving identical performance up to 350 knots and 7,000 feet. Above these speeds and altitudes, performance is very slightly lower although mechanical 'g' sensing provides a degree of the closed loop responsiveness present in the electionic version.

Infact, so successful has this mechanical version been that it may well be perferred for some of the advanced technology projects, for which the electronic version was created. It seems that the international financial climate is such that ultimate state-of-the-art sophistication is no longer the continuing aim and cost may even supercede lightness as the driver for some applications. Certainly the Mk16 mechanical Mode Selector equipped Mk16 ejection seat comes very close to the capabilities of the electronic version, although it cannot be integrated with the data-bus or provide some of the future developments foreseen for the electronic version.

It may be the case, however, that escape system technology has already met its cost ceiling and that future procurement agencies, outside the U.S. at least, will decide that NACES/Mk16 performance is good enough and that now attention will now be concentrated on acquisition and minimising life cycle costs and installed mass. We do not wish to speculate upon whether such a trend is beneficial to the development of future escape systems. We have however recognised the indisputable fact that low cost is becoming an increasingly powerful driver and we are developing alternative lightweight high performance Mk16 ejection seats to meet either market.

Historically 95% is the best aircrew recovery rate which has been achieved. If this can be maintained for future generations, then safety will have been well served.

POTENTIAL ROLE OF AVIONICS IN ESCAPE SYSTEMS

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SUMMARY

The role of avionics in escape systems for high-performance aircraft is rapidly expanding. In the most advanced systems currently in service, an electronic controller, in conjunction with mechanical sensors, selects the recovery sequence and controls event timing. More advanced avionics systems under development feature improved microprocessors and solid-state sensors. These slightly improve performance by modifying system timing based on airspeed and altitude conditions. They also introduce desirable "black-box" features such as built-in-test and fault isolation.

Avionics has the potential to contribute far more to escape systems based on the current development of controllable propulsion systems. Typically these systems would consist of multiple rocket engines under the command of a microprocessor/controller. The controllable propulsion system would control attitude and would also control the acceleration forces on the crew member. The avionics system would therefore include attitude and acceleration sensors. In "smarter" systems, the propulsion system could be used to control the escape trajectory for ground avoidance or to reduce forces on the crew member in an escape under benign conditions. Thus, the avionics system may include ground direction and proximity sensors. Real-time control of an escape system vehicle under the dynamic conditions associated with high airspeed or rapid maneuvering requires a comprehensive avionics system with high-frequency response. However, the technology is available, and this type of system could be a basic feature of any next-generation escape system.

INTRODUCTION

The avionics subsystem is the heart of the escape system since it controls the system functions. However, avionics is not the only critical subsystem. There must also be a data acquisition system to provide environmental information necessary for the avionics to determine the optimal flight plan, and a controllable propulsion system to carry out that flight plan. None of these subsystems can do much on its own, but when combined to form a complete escape system, they can provide a level of performance that has not previously been attainable. This performance gain is achieved mainly by the adaptive control provided in a real-time flight program. This capability will allow the development of escape systems that can be optimized for their entire escape envelope, not just portions of it. Figure 1 shows the basic control elements for an advanced escape system.

Modern digital systems under software control can provide an adaptive escape and recovery capability, not just a fixed order of events. Current escape systems execute a fairly simple, preplanned escape sequence based on limited environmental inputs. With an expanded array of input sensors and a powerful digital computer, future escape systems will be able to execute a real-time flight program. The dynamic conditions of the ejection can be continuously sensed and the flight plan adjusted accordingly. Thus, the variations in crew member weight, and the cg and aerodynamic forces can be compensated in real time.

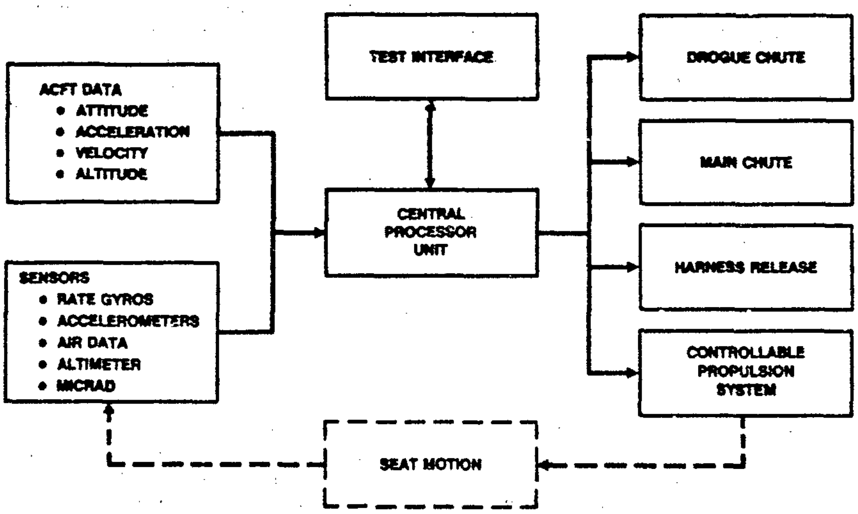

Figure 1. Control Elements

Other benefits of a digital system are an expanded built-in-test (BIT) and data recorder capability. The BIT will provide an improved test capability during both the actual escape sequence and the normal maintenance cycles. The data recorder can be designed as an integral part of the overall avionics system and provide valuable information for accident investigations.

LIFE THREAT ASSESSMENT

Current escape systems consider every ejection to have the same degree of risk. This is based on the assumption that if the crew member has elected to eject, it must be a real emergency and therefore the escape system must get him into a parachute as soon as possible. However, in the real world, this is not always the case. The risk level is related to how imminent ground (or aircraft) impact is, and how fast the aircraft is traveling. If the aircraft is in a steep dive at low altitude and high speed, the crew member is at high risk. If the aircraft is at high altitude and very high speed, the crew member is also at high risk. However, if the aircraft is at a moderate altitude, a moderate speed, and in level flight, the crew member is in a benign or low-risk situation. If the risk level is low, the avionics should attempt to provide an "easy ride" for the crew member. This means that the crew member should be subjected to low acceleration forces and little or no trajectory shaping. If, however, the risk level is high, the avionics must command the maximum allowable thrust levels within human tolerance in order to recover the crew member. This high-risk scenario will include maneuvers to avoid the ground, the aircraft, or other members of the crew. This type of real-time life threat assessment can be provided only by an advanced avionics system.

The actual acceleration limits for the various risk levels are based on the dynamic response (DR) model defined in Reference 1. This is a three-axis dynamic model of the human body that relates imposed acceleration forces to a probability of injury, assigned as low, medium, or high risk. Since the DR model is dynamic, it is dependent on the acceleration versus time history of the escape system rather than the static acceleration levels alone. The avionics must therefore balance the propulsive and aerodynamic forces in order to maintain the DR at or below the specified risk level, while at the same time maneuvering the crew member.

CONTROLLABLE PROPULSION

For the avionics system to achieve its full potential, it must be coupled with a controllable propulsion system. The basic requirements of a controllable propulsion system are: (1) variable thrust levels, (2) variable thrust vector, (3) variable burn time, and (4) high-frequency response. Such a propulsion system will allow the avionics to actually "fly" the escape system. Various systems are currently under development to provide this capability. Multiple solid-rocket motors and gel propellants are being investigated to provide a variable thrust level, while configurations utilizing fixed and movable nozzles are being developed to provide variable thrust vector control. Some systems utilize a movable main rocket nozzle supplemented by a series of reaction jets. The reaction jets provide a faster system response than is possible with a movable nozzle alone. A primary factor in the design for a controllable propulsion system is a high-frequency response. If the thrust vector cannot be moved quickly, the avionics will not be able to control the flight path of the escape system.

DATA ACQUISITION

An avionics system, no matter how "smart," must have a data acquisition system that can provide it with the information necessary for flight control. Pressure transducers can monitor the pitot and static pressures in order to determine the altitude and airspeed. Accelerometers and gyros can be used to provide an inertial measurement unit (IMU). If a ground avoidance capability is desired, a microwave radiometer (MICRAD) or radar altimeter could be added to the data acquisition system. Another source of flight information is the aircraft itself. At the time of ejection, the aircraft data bus could be interrogated to determine the initial ejection conditions. There is, however, a problem with using the aircraft data. The primary reason a crew member may decide to eject is the fact or perception that something is wrong with his aircraft. Therefore, the data coming from the aircraft may be invalid or suspect.

Because the integrity of the aircraft data will generally be in question, it is considered better to rely mainly on the data gathered by the seat-mounted sensors and use the aircraft only as a secondary source. Future aircraft may have the ability to determine their altitude above ground level (AGL), not just altitude above sea level. The AGL data could help the avionics to determine how imminent ground impact is, and allow it to begin a specific escape sequence based on data obtained before the crew member has actually ejected. However, the avionics must continue to do its own sensing in order to determine the validity of the AGL data from the aircraft. If the aircraft data cannot be confirmed by the escape system sensors, the avionics must rely on the data gathered from its own sensors.

Accuracy is a concern for all sensor data, not just the aircraft data. An avionics system without valid input data is, in effect, blind. For this reason, all sensor data must be checked and validated before use. With the software control available in digital avionics, this task can be performed with a high degree of adaptive logic. Current systems validate data by designing redundancy and reliability into the hardware of the sensors. Advanced systems must continue to provide redundant and reliable sensors, but the software can also allow the avionics to look at all the sensor inputs in relation to each other. If the air data sensors are indicating a low speed and the accelerometers are indicating a high deceleration rate, the software can initiate a self-test or perform additional logic checks in order to determine the most likely speed conditions. In the event that all the sensor data cannot be correlated, a generalized approach for the given conditions (e.g., a fail-safe approach) could be selected. Thus, in the event of a sensor subsystem failure, the escape system could revert back to a fixed-time, fixed-thrust recovery sequence that would perform much the same as current escape systems.

For the air data subsystem, conflicting input is the rule rather than the exception. In a typical escape system, a pair of total pressure ports is located in the headrest area. These ports are used to sense the total dynamic pressure acting on the seat. If the escape system were an aerodynamic body, both sensors would provide the same readings. However, experience has shown that the two pressure readings generally do not agree with each other. Typical causes of the pressure differences are turbulent airflow around the seat due to its blunt body, blanketing of a pitot from sideslip, and compressibility effects of local shock waves. Moreover, when the aircraft hatch or canopy is jettisoned, turbulence around the aircraft can cause the two pressure readings to differ. The solution to this particular problem is, however, fairly straightforward. It should be assumed that the highest total pressure reading is the correct one. The reason for this is that it is fairly easy to reduce the total pressure at the sensor, but it is difficult to increase it to a value above the free-stream maximum.

FLIGHT CONTROL

Current escape systems provide a fairly simple flight control that is intended more for stabilization than for actual guidance and control. Generally, a fixed main propulsion system is used in conjunction with a drogue parachute, or small aerodynamic fins, or both, to provide the stabilizing effect. The fins offer a partial solution, but are limited by size constraints imposed by the seat and cockpit geometry. A drogue parachute is a very effective means of stabilization; however, it develops its stabilizing moments by generating aerodynamic drag. At speeds above 600 keas, this drag force when added to the escape system drag force can cause deceleration loads that exceed the allowable human tolerance limits (DR). Some systems also provide active pitch control by means of a gyro-controlled vernier rocket. In any case, the total force acting on the system is relatively constant, and the only real variation is due to aerodynamic forces. With the flexibility provided by a controllable propulsion system, the total force on the system can be varied to meet the requirements of the ejection.

At high dynamic pressures, the aerodynamic loads on the crew member can exceed the human tolerance limits if his orientation is not precisely maintained. This is because open ejection seats are inherently unstable in yaw (Reference 2). With any slight perturbation, the seat will yaw, and at high speeds, a slight yaw angle will create high lateral g-loads, and a consequently high DR, on the crew member. Therefore, the first priority of the avionics must be to stabilize the crew member, and the second to maneuver him. Figure 2 illustrates the overall flow of a flight guidance system. When the crew member initiates ejection, the seat-mounted sensors will begin to determine the attitude and acceleration forces acting on him and perform a life threat assessment. As the escape system emerges into the airstream, the acceleration and angular rate data will be used to determine the counteracting moments that are required to maintain the seat in a stable attitude. After the seat is stabilized, additional thrust for maneuvering or counteracting the aerodynamic drag will be applied in accordance with the life threat assessment and the DR. This will provide a positive control force from the very initiation of the escape sequence, and will eliminate the need to wait for any type of deployable stabilization system to become effective. After the crew member has been stabilized and allowed to decelerate to an acceptable speed, either a drogue or the main recovery chute may then be deployed.

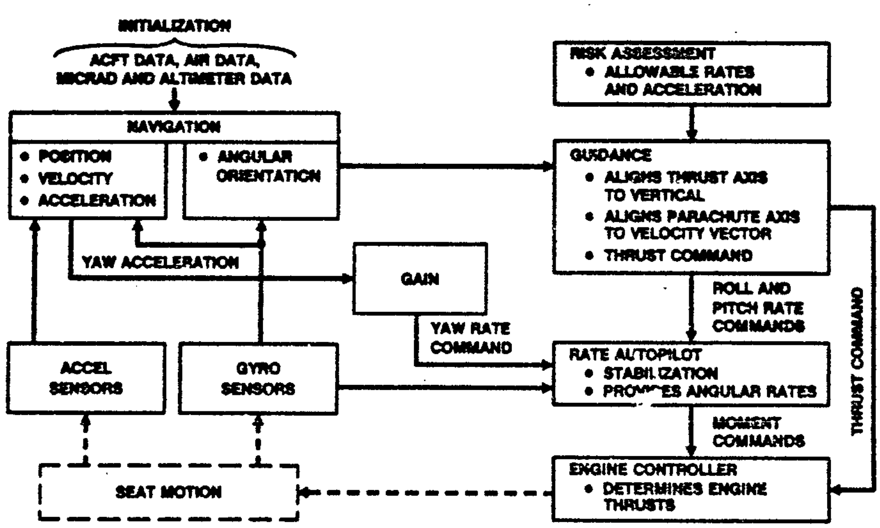

Figure 2. Guidance and Control Functional Flow Diagram

As stated previously, the allocation of stabilizing moments, maneuvering moments, and additional thrust required by the risk assessment must be balanced against the DR. For an escape trajectory to be optimal, it must maintain a DR value at or just below that associated with the risk level. This means that the avionics must continually perform real-time DR calculations and predictions based on the seat accelerations and the requested engine thrust. Because most propulsion systems do not have an infinite amount of thrust, the thrust management system must be capable of allocating the available thrust in order to perform the desired maneuver. This thrust management logic is illustrated in Figure 3. The highest priority is given to stabilization in the yaw axis, as this axis is the least stable and has the lowest acceleration tolerance limits. After the yaw stabilization requirements have been satisfied, the roll and pitch stabilization requirements will be satisfied. The last priority is to include any additional thrust required by the life threat assessment to perform the maneuver or counter aerodynamic loads. This logic will allow the escape system to expose the crew member to the minimum required loads in order to provide a safe recovery.

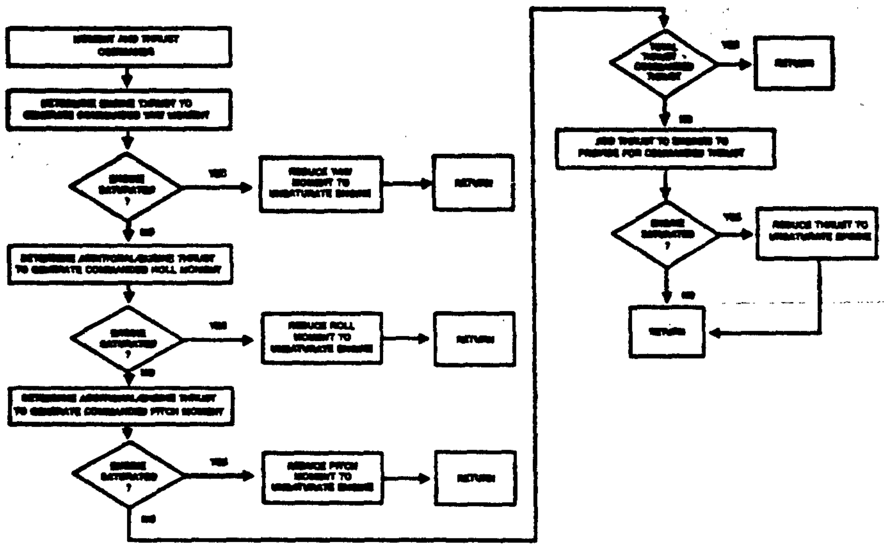

Figure 3. Engine Control Logic

Current escape systems do not feature a means of active ground avoidance other than minimizing the time to deploy the recovery parachute; that is, the distance traveled by the crew member is minimized by deploying the recovery parachute as soon as possible. Advanced systems will be able to sense altitude AGL, either from aircraft data or seat-mounted sensors, and determine the time of the impending ground impact. In a high-risk condition, the escape system will orient itself so that the maximum deceleration forces can be applied to the crew member in order to stop his downward velocity. This logic can also be extended to enable the crew members to avoid the aircraft and each other during egress. The geometry of the aircraft could be stored in the avionics and the escape system flight path compared to it. Thus, the escape system will be able to avoid the tail in a high-speed ejection, or the wing tip in a high-roll-rate condition. This type of decision-making logic will require the use of digital avionics in advanced escape systems.

CONCLUSIONS

Technological advances in the fields of digital electronics, solid-state sensors, and propulsion systems have opened the door for new escape system designs. New sensors will provide information that was previously unavailable, digital avionics will process that information in real time, and a controllable propulsion system will provide the muscle to safely recover the crew member. Any advanced escape system will require the integration of all three of these subsystems in order to achieve the full potential of each. However, it is the adaptive logic capability of the avionics that will allow the escape system designer to take this integrated system and make it deliver an order-of-magnitude increase in performance. By moving much of the decision-making and control functions from the hardware to the avionics software, escape system performance that was previously only a concept can now become a reality.

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Ejection Seat Training of Jet Pilots and Weapon System Officers at the German Air Force School of Aviation Medicine

by

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Ejection seat systems have been in use since World War II in most jet aircraft in Air Forces all over the world and nowadays have reached a high technical performance standard.

There is no doubt that any escape system can only be as efficient as its operator and user (being one and the same person!) and how he knows and correctly applies it within the system performance limits.

For these reasons academic and practical training of pilots and weapon system officers in two-seater aircraft has become mandatory.

The objectives of this training are as follows:
- Inform the pilot about the physical stress on his body during ejection from aircraft in order to safe his life and avoid injuries.
- Drill safe operating procedures of the respective escape system so they become routine and instinctive, emphasizing what can happen if the system is not used correctly or in good time.
- Eliminate the psychological threshold to actually get out of the protecting cockpit in case of emergency simply by having already practized this situation in a simulator.

For more than two decades the GAF IAM has used the Martin Baker Ejection Seat Trainer thousands of times to train aircrew on it.

The advantage of this Martin-Baker-Trainer was its very sturdy, simple construction powered only by a simple cartridge, which supplied the system with the required kinetic energy. After activating the system the trainee on his seat moved rapidly up an inclined guide rail after an ejection gun had been fired. The ascent was slowed down by gravity and brakes until a standstill was reached. Then the seat supported by a steel cable was slowly lowered to the bottom of the tower.
Increasing fair wear and tear, especially on the gun, and consequently decreasing acceleration, seat deficiencies - this seat never conformed to a genuine ejection seat - called for a new design. This new construction was undertaken by the German company Rhein-Flugzeugbau (RFB) in close cooperation with the GAF IAM, and is presently field-tested at our Institute.

The primary objective with this new device was to simulate ejection from the aircraft as realistic as possible under training conditions on the ground.

Attention should be paid to the following aspects:
- Training should be performed under medically safe conditions; i. e. accelerations encountered should not exceed about 2/3 of those experienced in flight ejections.
- Individual training ejections should be documented.
- Training should be economical.

Now let me give you a short description of the new training device and some first experiences with it. The equipment consists of the following main modules:
- a mobile trailer (low loader)
- raisable tower including a hydraulic power unit
- a carriage with exchangeable standard ejection seats, and
- a hydraulic and an electric control unit.

The entire system is mounted on a mobile trailer. This basic construction made of welded profiled steel provides the required trailer stiffness against torsion and bending. Prior to operation on uneven ground the trailer is levelled into the horizontal by means of hydraulic stabilizing chassis jacks. The 13 m tower is in stowed position for transport, rests on a welded pillow block and may be raised and lowered by hydraulics for operation. In its final up-position the tower has an inclination of 78 degrees. This corresponds to the angle at which the seat is ejected from the aircraft - related to the aircraft's longitudinal axis. A pressure oil accumulator with 200 bar serves as energy source. The power unit consists of a hydraulic cylinder with a piston. It is located at the lower portion of the tower. The movable piston accelerates the catapult sled including ejection seat and pilot - the movable mass is about 500 kg - along an elevatingdistance of one meter within 200 milliseconds at approximately 9 G. After this the sled plus seat and occupant is slowed down on the remaining distance only by gravity and comes to a halt after approximately 10 m. Arresting- and return devices protect the sled against overshooting or separation from guide rails and slowly return it to home position.

Hydraulic control and safety implementations protect against exceeding limiting values and damages. This type of propulsion is practically without fair wear and tear and contrary to pyrotechnical operations may be used again and again.
The catapult sled is designed in such a way as to accomodate any original ejection seat installed in aircraft using a quick-mounting device.

This gadget facilitates individual training:
Every pilot is trained on "his" seat. Thus the pilot is familiarized with the typical peculiarities. i. e. position of the firing handle, its shape and the resistance it offers.
These serial seats are aranged in the rear portion of the trailer. To transport them onto the sled we use a forklift.
The seats presently used are the S3S/STENCEL (in the Alpha-Jet), the GH 7/MARTIN BAKER (in the Phantom) and the MK 10/MARTIN BAKER (in the Tornado).
All future systems may be utilized. These seats have been only slightly modified, e. g. they have no survival kit, no O_2-emergency system or an emergency parachute respectively drogue. In contrast, however, the whole harness-power-retraction unit functions in the same way as in the original:

Upon activation of the system the upper body ist retracted at first. When the seat starts moving arms and legs are fixed. Feet and lower legs no longer rest on a moving and supporting footrest, but are suspended freely as in the real ejection situation. Thus the pilot gets a first hand experience about the benefits of a correct sitting posture.

Activation of the rescue system has also been modelled after realistic conditions: In a single-seater aircraft the pilot normally activates the system himself. In a two-seater, however, it may also be the back-seater who activates the system. In the ejection system in the aircraft is engaged on "BOTH", as it is the case if a jet passenger is in the back seat, then the pilot normally activates the system, and the rear seat fires first and is only then followed by the front seat some 200 to 900 milliseconds later.

On a single-seat trainer this is simulated in such a way that the training NCO assumes the part of the pilot by activating the system externally from transportable control board attached to his belly like a vendor's box.
There is always training in a group: one sitting on the ejection seat of the trainer, the others watching the sequence of the procedures, which would take place almost without any noise without the pyrotechnical firing.
To simulate the realisitc ejection the detonation bang is generated by electronics:
The synthesizer produces a realistic bang which is heard by everyone present via loudspeaker system. The ejection sequence is demonstrated with a double-bang. In this way the trainee experiences the front-rear ejection sequence acoustically: the seat starts moving only after the second bang.

Our training device is equipped with a little telemetric system: a G-meter is incorporated in the sled in such a way that the actual G-load is recorded via a small transmitter. Through a receiver unit the signal is plotted on an acceleration time-diagram. The record is provided with the ID-Number, the type of ejection seat used, and with the current day and time, and hence is an individual training document. The maximal acceleration and corresponding time is marked with cross hairs.

After approximately four months of practical training experience with this new device we found a much higher and better acceptance among pilots compared with the old system. The strange or funny look of this "blue monster" at first does not stimulate enthusiasm. But after the first shot the oldies especially verify that this type of training is extraordinary useful and even indispensable for them.

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THE USAF ADVANCED DYNAMIC ANTHROPOMORPHIC MANIKIN - ADAM

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SUMMARY

Ejection from aircraft at high speeds poses severe injury hazards to the crewmember. As performance characteristics of aircraft are further improved, the protection capabilities of ejection systems must also be improved to assure the safety of the crewmember. The demonstration of these ejection system improvements requires extensive testing with manikins to effectively evaluate the performance of the ejection seat and assess the injury potential to the crewmember. The United States Air Force (USAF) has embarked on a new effort to design and develop an Advanced Dynamic Anthropomorphic Manikin (ADAM) with improved human-like fidelity and data collection capability over currently available escape system testing manikins. This effort has resulted in the development and fabrication of two prototype (one small and one large) instrumented, anthropomorphic manikins for testing and evaluation and the production of ten manikins to be used in ejection and other protection system testing. Discussed will be the design objectives and resulting features of ADAM and a summary of testing results for exposure to extreme temperature and humidity environments; Gz low level vibration; and Gx, Gy and Gz whole body impacts.

INTRODUCTION

The use of mechanical human surrogates or manikins is becoming a more common and relevant approach for assessing the proper operation and safety of ejection and crash protection systems and procedures. Early manikins were developed to provide inertial loading similar to that of the human body and were primarily used to test the proper operation of harnesses, seat structures and ejection seats. In these tests the concern was with the response of the equipment as affected by the inertial effects of the human body. Typical manikins used for such applications were developed by Sierra and Alderson in the 1950s primarily to provide human-like ballast for ejection seats. While their overall mass distribution properties were quite good, their joint mobility and body flexibility were very limited. This resulted in highly rigid responses to external forces and internal dynamic measurements that did not compare well to human responses for similar exposures.

A new generation of manikins was developed in the 1960s and 1970s, primarily driven by increased emphasis on road motor vehicle safety. The most common of these is the Hybrid II manikin originally developed by General Motors and adopted by the National Highway Traffic Safety Administration as the standard automotive safety compliance testing manikin. This manikin, most commonly known as the Part 572, had considerably improved human-like fidelity. It was designed to provide internal response measures that could be correlated to equivalent human responses and possibly, the likelihood of injury. Several other manikins were developed in the United States, Great Britain and Sweden in this same time period that attempted to improve response characteristics, but none achieved the degree of standard acceptance as had the Part 572 manikin. In the late 1970s General Motors developed the Hybrid III, which had improved biofidelity and instrumentation capability over the Hybrid II.

This evolutionary process did improve the state-of-the-art in manikin design sophistication, biofidelity and response measurement capability. Most of it, however, was directed at road vehicle safety design considerations with considerable emphasis on chest and head impact responses, horizontal impact events and testing under highly controlled conditions. Attempts to use these types of manikins in aerospace environments led to the identification of a number of shortcomings. These included (1) the lack of proper dynamic longitudinal spinal axis response (the predominant loading direction for aircraft related force exposures), (2) the use of an umbilical cord for data retrieval requiring a separate data acquisition system which in turn limits the freedom of manikin motion and (3) durability sufficient only to withstand relatively low forces compared to those encountered in aircraft crashes or escape from aircraft.

To address these shortcomings, the USAF has pursued the development of an Advanced Dynamic Anthropomorphic Manikin (ADAM) to be used in the testing of escape systems and various crew protection systems and procedures. Its first testing application will be in the USAF Crew Escape Technology (CREST) advanced ejection seat, where it will be used to validate the operation of the vectored

Table 1

1	Left Hip Abduction/Adduction Position
2	Right Hip Abduction/Adduction Position
3	Left Hip Flexion Position
4	Right Hip Flexion Position
5	Left Hip Medial/Lateral Position
6	Right Hip Medial/Lateral Position
7	Left Knee Flexion Position
8	Right Knee Flexion Position
9	Left Knee Medial/Lateral Position
10	Right Knee Medial/Lateral Position
11	Left Shoulder Arm-Joint Abduction/Adduction Position
12	Right Shoulder Arm-Joint Abduction/Adduction Position
13	Left Shoulder Thorax-Joint Abduction/Adduction Position
14	Right Shoulder Thorax-Joint Abduction/Adduction Position
15	Left Shoulder Flexion/Extension Position
16	Right Shoulder Flexion/Extension Position
17	Left Shoulder Medial/Lateral Position
18	Right Shoulder Medial/Lateral Position
19	Left Arm Raising/Lowering Position
20	Right Arm Raising/Lowering Position
21	Left Elbow Flexion Position
22	Right Elbow Flexion Position
23	Left Forearm Supination/Pronation Position
24	Right Forearm Supination/Pronation Position
25	Left Lower Leg Torque
26	Right Lower Leg Torque
27-32	Neck Forces and Moments (6 axis)
33-38	Lumbar Forces and Moments (6 axis)
39-41	Head Acceleration (triaxial)
42-44	Head Rotation Rate (3 axis)
45-47	Chest Acceleration (triaxial)
48-50	Pelvis Acceleration (triaxial)
51-52	Parachute Loads, Right and Left Risers
53	Temperature Measurement
54-56	Lumbar Position
57	Viscera Position
58	Viscera Acceleration
59	Sternoclavicular Elevation/Depression Position
60	Sternoclavicular Protraction/Retraction Position

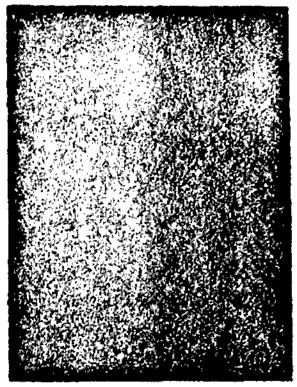

Figure 1 Small ADAM

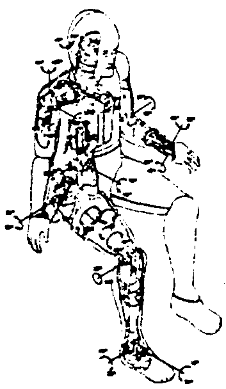

Figure 2 ADAM Joint Ranges of Motion

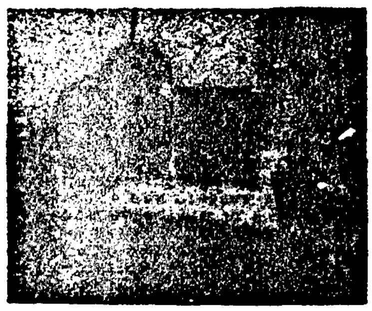

Figure 3 Measurement of ADAM's Lower Leg Mass Properties

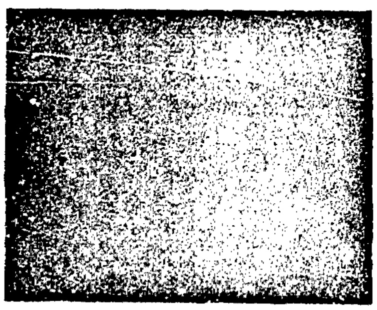

Figure 4 ADAM Knee Joint Showing Flexure and Torsion Articulations, Friction Pads and Wire Connections to Position Measuring Potentiometers

Figure 5 ADAM Shoulder Joint Showing Multiple Revolute Articulations

thrust rocket ejection seat under realistic human-like payload conditions. The manikin development effort was initiated in September 1985 and has resulted in the fabrication of a small and a large prototype manikin. Design emphasis has been on the manikin providing a human-like reactive load into the ejection seat and possessing realistic dynamics and kinematics due to windblast, impact, vibration and acceleration forces representative of those encountered during ejection from aircraft.

ANTHROPOMETRY

The small and large ADAMs are based on a USAF male aviator anthropometric survey conducted in 1967 with the specific dimensions and inertial properties taken from tri-service (US Army, Navy and Air Force) recommendations. They are based on multiple stature and weight regressions on the 1967 USAF male flying personnel survey data corresponding to approximately 3rd and 97th percentile individuals with a projected time growth factor for the year 1990 (Ref. 1). The manikin body has 17 articulating segments consisting of the head, neck, upper arms, lower arms, hands, thorax, abdomen, pelvis, upper legs, lower legs and feet. Figure 1 shows a small ADAM with skin coverings in place. The design requirements included (1) articulating joints for the shoulders, elbows, wrists, hips, knees and ankles as well as articulations for the spine, including the neck, (2) appropriate joint ranges of motion and joint resistance properties, (3) weight of each body segment along with the total body weight for both manikin sizes to be within the tri-service specifications, (4) segment surface contours to conform as much as possible with corresponding human shape for each size manikin, (5) segment moments of inertia, centers of gravity locations, and joint centers of rotation to be within the tri-service specifications (Ref. 2). Figure 2 shows the ADAM joint ranges of motion. Figure 3 illustrates the use of the Space Electronics Mass Properties Measurement System used to determine the center of gravity and moments of inertia of all the ADAM segments.

JOINT STRUCTURE

The design for ADAM stresses faithful human joint articulation and torso axial deformation to properly reflect the mass shifts and limb motion, as well as dynamic spinal compression, that an actual crewmember would experience during a whole body abrupt acceleration and windblast exposure. ADAM has articulating joints for the shoulders, elbows, wrists, hips, knees and ankles as well as articulations for the lower spine. All the joints with the exception of the neck and spine, are single or compound revolute joints with precisely defined axes orientations, joint stops with soft snubbers, adjustable friction pads for joint resistance and position sensing potentiometers. These features can be seen for the knee and shoulder joints in Figures 4 and 5, respectively. A standard Hybrid II manikin head and a Hybrid III neck were used. The axial spine element is a combined spring and hydraulic damping element which is tuned to provide longitudinal impact response with a natural resonance in the .0 to 12 Hz range. Re-tuning may be accomplished by spring replacement and use of a different viscosity hydraulic fluid. Below the axially deforming spinal element is a universal joint that allows for yaw motion as well as flexural and lateral bending. This compound articulation is approximately in the lumbar anatomical region and provides the only bending articulation in the torso. The total spine structure is shown in Figure 6.

INSTRUMENTATION DESIGN

The total instrumentation and data acquisition system for ADAM is a substantial advancement over any other current manikin. A Motorolla 68020 32-bit microprocessor controls the entire data acquisition process and is located in the thorax. The instrumentation system provides for signal conditioning, analog to digital data conversion and pre and post test calibration of each channel. The system interfaces with many different types of sensors including accelerometers, pressure gauges, velocimeters, strain gauges, temperature sensors, position sensors and the like. In its standard configuration, the system can collect 128 channels of sensor information at 1000 samples per second per channel (72 channels with full signal conditioning on the manikin and 56 preconditioned channels external to the manikin). All 72 ADAM channels have individual anti-aliasing low-pass filters with computer controllable cutoff frequencies up to 200 Hz. The system configuration can be modified by a hand-held diagnostic unit to change the number of channels, the sampling rate and the filter bandwidth. The instrumentation system has 512 kilobytes of static random access memory (RAM) to store test data and has an internal back-up power source to prevent data loss if power is inadvertently lost after a test. Data can also be collected during a test using an on-board pulse code modulation (PCM) telemetry transmitter and a head mounted antenna. This technique can be used with a landline link or with a radio link to a receiving station. During a dynamic test, data can be telemetered in near real time via the on-board telemetry transmitter and/or stored in on-board memory for download following completion of the test. Shown in Figure 7 is a small ADAM with the upper torso, right arm and right leg skins removed to show the instrumentation package located in the thorax area, a battery storage compartment in the upper leg and the head mounted antenna used for data transmission. The circuit board configuration, from the rear view, is shown in Figure 8.

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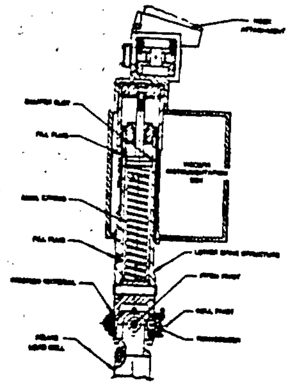

Figure 6 ADAM Spine Structure

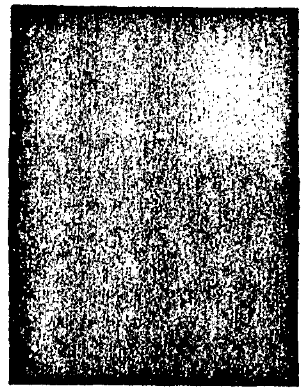

Figure 7 Small ADAM with Skins Partially Removed to Show Instrumentation Package in Thorax Area

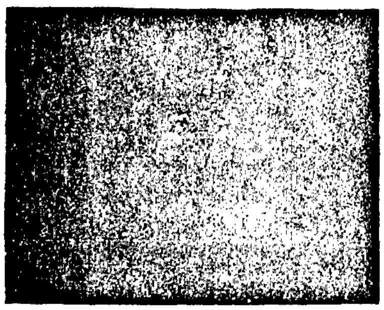

Figure 8 ADAM Instrumentation Package with Rear Access Panel Removed

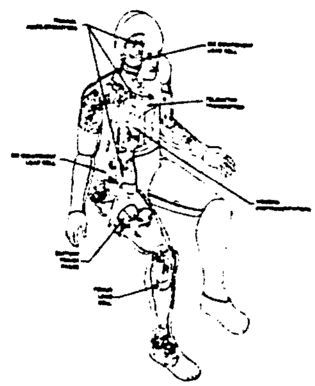

Figure 9 ADAM Instrumentation and Transducers

Figure 10 ADAM Support Equipment

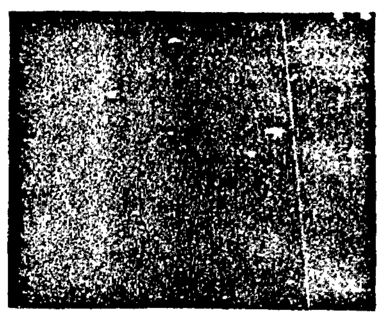

Figure 11 Vibration Test Facility

The availability of 128 channels of data allows extensive monitoring of the manikin's responses as well as collection of external data. ADAM has been designed for measurement of three orthogonal acceleration components (tri-axial) in the head, thorax and pelvis; six force and moment components both between the head and the neck and between the lumbar spine and the pelvis; and the position of all revolute joints. Additionally, load cells are located at the joints in the lower legs to measure torsional moments. Figure 9 shows the location of a number of ADAM transducers. A listing of these transducer channels, including ones for internal temperature and parachute riser loads, are presented in Table 1.

Four pieces of primary support equipment can be used with the ADAM's instrumentation system. They are the Field Power Supply, the Decommutation System, the Data Retrieval and Storage System and the hand held Control and Diagnostic Unit.

The Field Power Supply (FPS) is a rechargeable power supply that was designed to supplement ADAM's on-board batteries. The FPS contains its own rechargeable battery which electronically circumvents ADAM's on-board batteries whenever it is connected and placed on-line. The Decommutation System is used as a landline telemetry link for real-time data acquisition during tests and as a diagnostic tool for the on-board telemetry system. The Data Retrieval and Storage System (DRASS) off-loads data from ADAM's on-board memory and stores the data. A high speed parallel port is located on ADAM's instrumentation system to download data to the DRASS, which takes approximately four seconds. The DRASS is the link between ADAM and a device for permanent data storage and/or analysis. The DRASS can communicate with a wide variety of computers, printers and terminals using a standard RS-232 or RS-422 serial port at various baud rates. The hand held Control and Diagnostic Unit (CDU) is used to access a comprehensive set of diagnostics to test the system operation and to provide assistance in system calibration and hardware trouble shooting. Figure 10 shows the ADAM with its support equipment.

ADAM COMPLIANCE TESTS

ADAM was subjected to a series of rigorous tests to ensure that it performs to the design specifications. The tests were designed to duplicate the environmental conditions to which ADAM will be subjected during an ejection test at Holloman AFB NM in support of the CREST development program. This section describes a number of tests conducted by the USAF to evaluate ADAM. It also provides a summary of the tests, but is not meant to be an in-depth test report since many of the tests have recently been completed and further data analysis is still to be performed.

Gz Vibration Tests. The Gz vibration tests were conducted to determine ADAM's spinal dynamic response and to test the functional integrity of the instrumentation system under vibration conditions. The tests were conducted on an Unholtz-Dickie vibration table (Figure 11). Data collected in the tests included the force between the seat and vibration table, velocity of the seat, and driving point impedance (magnitude and phase) between the manikin and the seat. In the first series of tests the frequency range covered was 3 to 30 Hz in 1 Hz discrete increments and at low acceleration levels (Small ADAM - 0.2 and 0.4 G and the large ADAM - 0.2, 0.3 and 0.4G) typical of those used for human impedance measurement testing. In the second series of tests, the primary concern was the ADAM instrumentation system durability and possible mechanical resonances from 30 to 200 Hz that might lead to structural electrical system damage. Preliminary test results indicated a resonant frequency of approximately 12 Hz for the small ADAM and 9 Hz for the large ADAM. These values correspond to the 10 Hz natural resonance frequency designed into each manikin for spinal dynamic response. No structural system damage or data collection problems were encountered during the vibration tests.

Vertical Drop Tower Tests. The primary purpose of these tests was to evaluate the durability of the ADAM mechanical structure, sensors and data collection system for Gz impacts up to 24 Gs and to determine the degree of improvement in dynamic response simulation provided by the ADAM versus the manikin currently used for ejection seat tests, the Grumman-Alderson Research Dummy (GARD). Since the ADAM will be used to evaluate the performance capability of the CREST technologies demonstration seat, it was vital that the dynamic response properties of the ADAM be measured in a realistic context. Therefore, the use of seat cushions and restraints associated with CREST were used in the tests. A rather extensive program was conducted to determine not only how ADAM responds to vertical impacts, but also how humans and the GARD manikin respond under the same impact conditions. The following tasks were performed as part of this program: (1) measurement of the dynamic response of the human body during +Z-axis impact with seat-back angles of 0 and 10 degrees, (2) measurement of the dynamic response of the ADAM prototypes during +Z-axis impact with seat-back angles of 10, 0 and -10 degrees, (3) measurement of the dynamic response of the GARD manikins during +Z-axis impact with seat back angles of 10, 0 and -10 degrees, (4) measurement of the dynamic response of human subjects, the ADAM prototypes and the GARD manikins with and without seat cushions, (5) measurement of the dynamic response of human subjects, the ADAM prototypes and the GARD manikins with the CREST X-band 90 degree and

PCU-15/P restraint harnesses, (6) demonstrate the structural integrity of ADAM prototypes and instrumentation systems and (7) demonstration of the functional capability of the ADAM instrumentation system.

A generic seat was used during the tests that was fully instrumented to measure seat deceleration, loads applied by the test subject to the seat back and pan and harness tie-down loads. The tests used the CREST X-band 90 degree and the PCU-15P harness to restrain the test subject and were attached to the test fixture through load cells so that subject-applied harness loads could be measured. Eight channels of ADAM data were recorded through three different paths and measured: (1) Head X acceleration, (2) Head Z acceleration, (3) Chest X acceleration, (4) Lumbar Z acceleration, (5) Lumbar Z force, (6) Neck Z force, (7) Right knee flexion and (8) Left elbow flexion. These eight ADAM data channels were connected in parallel to the Automated Data Acquisition Control System (ADACS) of the test facility which served as a standard for comparing data obtained by the following two methods. The data from these same channels were obtained from the output of the telemetry port of the ADAM system and from the on-board ADAM memory system. Comparison of the data recorded by these two different methods against the standard (ADACS) was used to provide an evaluation of the functionality and accuracy of the ADAM's telemetry and memory systems.

Horizontal Impact Tests. The specific objectives of these tests were to (1) demonstrate the ADAM structural durability and data acquisition system reliability (comparing data obtained via the ADACs, ADAM on-board memory and telemetry), (2) measure the dynamic response of the ADAMs during -X-axis and -Y-axis impacts by measuring the restraint load-time histories and body motion and then comparing it to existing human test data and (3) demonstrate the stability of the ADAM electronics with respect to pre-test sensor sensitivities.

All the tests were conducted using the AAMRL Impulse Acceleration facility at Wright-Patterson AFB OH. The experimental test fixture was the "40-G seat" on a 17 degree wedge (used in -X-axis testing only), mounted on the Impulse Acceleration sled and modified to represent the CREST seat in an F-16 configuration. For the +Y-axis tests, the seat back was reclined 13 degrees from the vertical. The X-Band 45 degree restraint harness and the X-Band 90 degree restraint harness were used for all tests. Each manikin contained the following sensors: tri-axial linear accelerometers mounted in the head and chest, six-component load cells mounted in the head/neck and pelvis and an externally mounted tri-axial chest accelerometer. Photogrammetric data was recorded during each test by high speed cameras mounted on the sled at oblique and right angles to the manikins. Preliminary results have demonstrated that both ADAMs successfully passed tests of up to 45 Gs -X-axis and 14 Gs +Y-axis impacts without permanent deformation or failure of mechanical structures and the instrumentation system operated and maintained structural integrity.

Environmental Tests. This series of tests was designed to expose ADAM to an environment similar to the one it is to operate in. The main objective of the thermal tests was to evaluate the functional integrity of the instrumentation system under thermal conditions for temperature ranges of 32 to 158 degrees Fahrenheit (0 to 70 degrees Centigrade) and humidity ranges of 0 to 98 percent relative humidity. The small ADAM was placed in an environmental test chamber and exposed to the following combinations of temperature and humidity: 1) high temperature and high humidity, 2) high temperature and low humidity, 3) low temperature and high humidity, and 4) low temperature and low humidity. Each test was four hours in duration. ADAM data was collected from both the on-board memory and from the telemetry output. Comparison of the data recorded by the two sources was used to provide an evaluation of the functionality and accuracy of the ADAM telemetry and memory system during extremes in temperature and humidity. One problem was discovered during the tests. At approximately 140 degrees Fahrenheit, with the manikin fully powered, the central processing unit failed. At the time of failure the internal temperature in the instrumentation enclosure caused by heat buildup was 220 degrees Fahrenheit. While th central processing unit failed at this temperature, no permanent damage resulted and total functional recovery occurred after system cool down. Further tests are planned to investigate this problem. Cooling devices may need to be installed in the instrumentation enclosure to dissipate heat for operation in high ambient temperatures. Cold temperatures and varying humidity levels did not affect the operation of the instrumentation system.

SUMMARY

The ADAM has been designed not only to provide correct reactive loads into the harness, seat and any other interactive structures, but to also be sufficiently internally biofidelic so that its internal response measures may be related to equivalent human responses under the same exposure conditions. The information acquired from ADAM will provide unique and valuable insights into the responses of the combined ADAM and ejection seat system to high-speed windblast, impact, vibration and acceleration forces. Perhaps more importantly though, it also will provide evidence as to how these combined forces will affect the crewmember and allow a realistic assessment of his changes for survival. While substantial validation still needs to be performed, the biofidelity and extensive response measurement capability of ADAM should make it a powerful tool for the safety assessment of aircraft subsystems and procedures.

Future refinements to ADAM currently underway include developing composite segments for more anatomically correct inertial and bone-like deformation properties and an improved neck to provide more human-like responses in forward and lateral impact directions.

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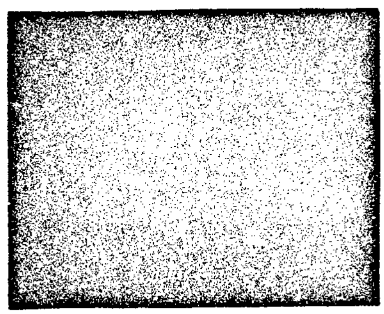

Figure 12 ADAM -45 Gx Horizontal Sled Run

Windblast Protection for Advanced Ejection Seats

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SUMMARY

The United States Air Force is currently engaged in an advanced development program to demonstrate the feasibility of extending the capability of open ejection seats to 700 KEAS. The probability of injury at this airspeed is estimated to be 100 percent, based on the current injury statistics. Past approaches to windblast protection have involved the use of harnesses and limb tethers which have proved to be unacceptable to pilots. Therefore, advanced unencumbering techniques are required to provide the needed protection. The USAF has developed and tested a windblast protection concept that utilizes high-strength, deployable fabric panels. The panels capture and slow the aerodynamic flow impinging on the ejection seat occupant's extremities and torso and reduce the probability of windblast induced flail injury. Wind tunnel tests were conducted in low- and high-speed wind tunnels using one-half scale models of a fiftieth percentile crewman and ejection seat as well as full-scale manikins and modified ACES II ejection seats equipped with the flow-stagnation panels. The tests were accomplished to determine the degree of protection for the crewmember, the influence of the flow-stagnation panels on ejection seat aerodynamics, and the effects of design changes to the panel shape and material. The wind tunnel tests have demonstrated the protective potential of the flow-stagnation concept, but classical aerodynamic and windblast tests have indicated the configuration of the panels is critical to the protection of the crewmember's head. Configuration of the panels is also critical for the reduction of the total loads acting on the crewmember and seat combination. Without passive aerodynamic reduction of the forces and moments, a larger catapult and stabilization system thrust must be used to maintain stabilized flight through the ejection sequence. An overview of the flow-stagnation windblast protection system tests, the implications of its use and required future tests are discussed.

INTRODUCTION

An unfortunate George Smith was forced to eject from his F-100A over the Pacific Ocean on February 26, 1955. The altitude at the time of ejection was between 5000 and 7000 feet. The aircraft was travelling at 675 KEAS in a near vertical dive meaning that Smith encountered dynamic pressures in excess of 1500 pounds per square foot (psf) during his entry into the airstream. As a result of his experience, Smith received multiple injuries but none of them proved to be fatal. These included internal hemorrhage, concussion, hip joint sprains, and an intestinal obstruction due to a perforation of the intestine which was believed to occur during the ejection as well as a plethora of other minor ailments. Following his accident, researchers made the first attempt to quantify the forces and accelerations endured by the pilot and correlate them to the actual injuries sustained. A series of high-speed sled runs was conducted at the Air Force Flight Test Center, Edwards Air Force Base to measure seat and manikin accelerations and calculate the forces occurring during test ejections designed to simulate Smith's experience (1). It was concluded that the medical findings were consistent with the pattern of accelerations and forces calculated during the simulated ejection tests.

Surveys conducted later were more complete in describing the relationship between aircraft speed at the time of ejection and injuries sustained (2). Statistical ejection data from United States Air Force (USAF) was used to relate the frequency and severity of windblast injuries to aircraft speed. Given the average speed of ejection as determined from this study, 225 knots indicated airspeed (KIAS), the expected injury rate was only 3 percent. However, if this figure were to increase by 50 knots, as in the case of combat situations where slowing to optimum speeds before escape is not possible, the injury rate would rise to 7 percent. A further increment of 50 knots to 325 KIAS would result in a 13 percent incidence of flail injury. Also, the average speed of ejection resulting in major injury was found to be 414 KIAS for USAF ejection experience through 1970. The analysis clearly shows that injuries caused by the forces and accelerations during ejection have the potential for increasing in a nonlinear fashion to a point at which there is a 100 percent certainty that an ejecting crewmember will receive a windblast injury above 600 KIAS.

Other researchers have investigated the correlation of ejection-induced or windblast injury and USAF ejection experience to produce a "probability of flail injury" curve as a function of aircraft speed at the time of ejection (Figure 1). Payne described the relationship between flail injury and ejection airspeed and demonstrated that the probability of flail injury is normally distributed by the square of the indicated airspeed (3). In 1978, Belk categorized flail injuries against aircraft type, airspeed at the time of ejection, method of initiation of ejection (sequenced, D-ring, face curtain, sidearm, or inadvertent) and presence or lack of restraint systems designed to prevent flail injuries. The resulting injury curve. that were generated show the same relationship between the probability of flail injury and ejection airspeed that the earlier analyses produced (4). Belk's work also showed, however, that the average ejection airspeed was increasing with newer aircraft. This resulted in an increase in flail injury as predicted by the probability of injury curve versus ejection airspeed. It appears that the occurrence of windblast injury would be a limiting factor in judging the performance capabilities of emergency ejection seats. Windblast countermeasures will be essential if these capabilities are to be extended to higher airspeeds.

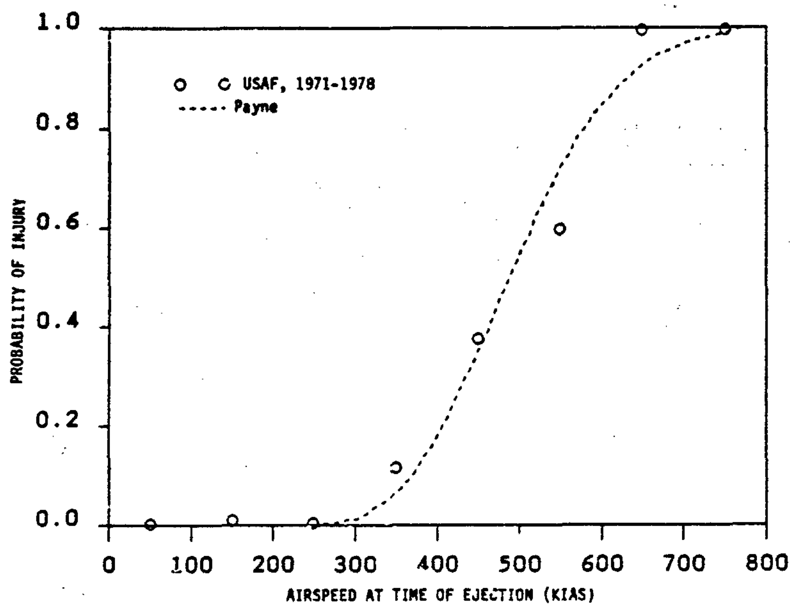

FIGURE 1. PROBABILITY OF INJURY VS. EJECTION AIRSPEED

PHYSICS OF WINDBLAST RESPONSE

Understanding the physical processes that occur during windblast injury are necessary in order to design an effective countermeasure. Fortunately the physical processes which produce windblast injury are well understood (5). There is great disparity between the forces acting on the extremities of an ejectee and those acting on the seat during ejection into a high-velocity windstream. The limbs are forced outward (to the side) and backward due to the direction of the aerodynamic flow, and because of their higher drag characteristics they decelerate more rapidly than the torso and seat. If the arms and legs are dislodged from the seat by the aerodynamic and inertial forces and if the airspeed is sufficiently high, the extremities are injured when joint strength is exceeded or when the long bones are fractured by contact with the seat structure. Injury of the cervical spine is caused by tension, bending, and/or shear loads resulting from inequalities of the aerodynamic forces and accelerations acting on the head and neck.

PROTECTION TECHNIQUES

Solutions to the problem of preventing windblast injuries include many ideas on restraining the motion of all extremities and reducing the loading occurring on the limbs by altering the aerodynamic flow as well as reducing the inertial loading. Conventional approaches to windblast protection have used extremity restraints such as leg garters and arm sleeves with encumbering straps which must be donned and attached to the seat. Head and neck protection concepts have restricted mobility, added bulk, presented actuation problems, and frequently created added injury hazards. Therefore, conventional windblast approaches have not been readily accepted.

The approach to crew protection for emergency escape at high airspeeds has been encapsulation of the ejection seat (as in the B-58 and B-70 escape systems) or use of a separable cockpit as an escape vehicle (as in the F/FB-111 aircraft). However, both systems have considerable weight, cost, and low-altitude performance penalties. Therefore, new approaches are being considered to reduce the risk of windblast injuries in open ejection seats. These include the use of both active restraint, requiring the occupant to take action to don the system, and passive devices that provide protection by reducing the aerodynamic flow impinging on all or a portion of the seat-occupant's body.

State-of-the-art ejection seat stabilization is a major factor that constrains the design of an effective windblast protection system. Wind tunnel test data and the results of rocket sled tests have demonstrated that ejection seats have not achieved adequate directional stability at high-speed. This problem severely compromises the effectiveness of side panels and nets which are mounted to the sides of the seat and intended to prevent extremity flail injuries. However, directional control has been improved in the recent generation of ejection seats and further advancements are anticipated in the next decade. Therefore, protection schemes predicated upon improved seat stabilization may have merit as longer term solutions.

THE FLOW-STAGNATION CONCEPT

The USAF has developed and tested a windblast protection concept that utilizes high-strength, deployable fabric panels (6). The panels capture and slow the aerodynamic flow impinging on the ejection seat occupant's extremities and torso, and they reduce the probability of windblast-induced flail injury. This captured air, or stagnated flow, then diverts the high-velocity airflow around the seat occupant. The crewmember sits in the flow-stagnation region which eliminates the large differential pressures which would act to dislodge his limbs. One of the flow-stagnation configurations currently being studied uses a fabric fence erected around the seat-occupant's head, torso, and upper legs prior to ejection (Figure 2).

OVERVIEW OF FLOW-STAGNATION PROGRAM

The effectiveness of the flow-stagnation concept has been evaluated by wind-tunnel tests utilizing both scale-models and full-scale test ejection seats equipped with panels and operational hardware. The scale-model tests were accomplished to determine the concept feasibility, the loads acting on the crewmember, Mach number effects and the effects of panel size on the amount of protection given to the crewmember. The full-scale tests were run to evaluate the effects of the flow-stagnation panels on seat performance.

During the scale model tests, a one-half scale model of a crewmember and ejection seat was used. The size of the stagnation fence was varied from an estimated maximum feasible size to 25 percent of those dimensions. The maximum-size fence configuration protruded 12.5 in forward above the occupant's helmeted head, 9 in forward at mid-helmet level, 9 in forward at upper-arm level, and 6.75 in upward from the seat sides by the lower-arm (full-scale dimensions).

The data collected during these tests indicated that the flow-stagnation fence is very effective. Pressure measured at various points within the cavity bordered by the fence showed the degree of stagnation ranged from 80 to 100 percent when the maximum fence was used and 50 percent when the fence dimensions were reduced by one half. The pressures measured on the seat-occupant's helmet visor and chest were raised only slightly since these areas are normally regions of stagnated flow. The loads measured by the force-measuring devices within the seat-occupant model showed major reductions when the flow-stagnation fence was used. For example, previously measured vertical forces of approximately 1000 pounds acting on the head were reduced to near zero over the range of pitch angles tested. The axial forces acting on the head were reduced to near zero when the fence size was 50 percent and were negative with the maximum-dimension fence. Negative forces indicate that the force was now acting in the opposite direction. The sideward forces acting on the head and arms were also reduced. The stagnation fences affected the vertical force on the lower arms in the same manner as the head.

Forces and moments measured to evaluate the influence of the fence on the aerodynamic properties of the model revealed several significant changes in the stability characteristics. First, the pitching-moment coefficient was reduced. This is a beneficial effect since the model without the fence has a significant negative pitching moment. Second, the addition of the fence had practically no influence on the yaw moment. Third, the drag coefficient of the model nearly doubled when the maximum size fence was used and increased by 75 percent when the fence size was reduced by one half. Fourth, the force coefficient acting perpendicular to the wind vector increased from -0.11 to -0.58 when the full-size fence was added. Reduction of the fence size by one half did not produce a major change in this effect.

Mach number also had a significant effect on the aerodynamic forces acting on all the limb segments of the basic model. The limb forces generally increased with increasing Mach number. However, when the flow-stagnation panels were added, the limb forces were reduced again to nearly zero. Although the lift values for the head increased slightly with increasing Mach number, the values remained low in magnitude. The protection afforded by the flow-stagnation panels was effective for all limbs up to speeds of Mach 1.2 (7).

The crewman/seat model was not believed to be a reasonable indicator of seat performance characteristics with the flow-stagnation panels attached. Since the crewmember's limbs were extensively instrumented, the flow-stagnation panels were purposely built outboard of the arms so that there was no possibility of interference. Interference between the flow-stagnation panel and limb would have altered or made the measurement impossible. The mounting structure for the flow-stagnation panels was reasoned to increase total seat drag and normal forces because of the increased projected frontal area. These increased loads would tend to increase already high deceleration loads and sink rates. A larger catapult and rocket motor would be required to compensate for these effects, and the weight and volume requirements for the additional propellants would preclude the use of the flow-stagnation panels.

To circumvent the difficulties of using instrumented scale models to evaluate the effects of the flow-stagnation panels on seat performance, full-scale tests were conducted. Prototypes of the flow-stagnation panels were fabricated and attached to an ejection seat. A total of seven flow-stagnation configurations were tested during two wind-tunnel test series. Human subjects were used during the test program and were outfitted with minimal flight gear. The full-scale static aerodynamic coefficients that were found with a flow-stagnation configuration similar to the one tested on the scale model, indicated significant improvement. For example, the total seat drag was 40 percent greater than the drag measured for the baseline. The same measurement for the model indicated a 100 percent increase. The normal force coefficient showed a positive increment over the baseline configuration. The remaining aerodynamic coefficients reflected the trends observed in the scale-model wind tunnel tests.

Further investigation of the high drag values was accomplished with the use of smoke injections into the windstream. The smoke was injected upstream of the model, and the flow over the model was observed. With the baseline model (no flow-stagnation panels) the smoke was swept around the crewmember and was quickly dissipated behind the seat into a low-pressure region. The smoke flowfield swept a different apparition when used on the model fitted with the flow-stagnation panels. The smoke was observed to dissipate almost immediately to the side of the panel after it passed the leading edge. This was an indication that the low-pressure region was larger for the flow-stagnation configuration than that of the baseline. If the airflow separation were moved downstream, the low-pressure region could be reduced or eliminated and the total drag acting on the seat/crewmember combination would be reduced.

Follow-on, full-scale wind tunnel tests were designed to shift the point of airflow separation aft of the leading edge of the flow-stagnation panels. Principles of thrust vectoring were used to locate vent locations along the flow-stagnation panel where the flow separation was observed to occur. The venting allowed the high-pressure airflow from within the stagnation volume to enter the separated region along the side of the seat, re-energize the boundary layer, and delay flow separation. Three vented configurations were tested with each configuration allowing more venting than the previous one tested. The third configuration had venting locations at the leading edge of the flow-stagnation panel, mid-panel and rear edge of the panel (Figure 3). The total drag of the crewmember and seat combination was significantly reduced for these configurations. Improvements of 26 percent in total drag were measured for the three-vent configuration. The drag or axial force coefficient values for the various panel configurations are shown in Figure 4.

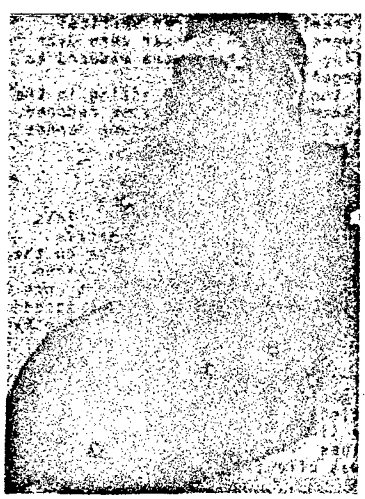

FIGURE 2. FLOW-STAGNATION CONCEPT

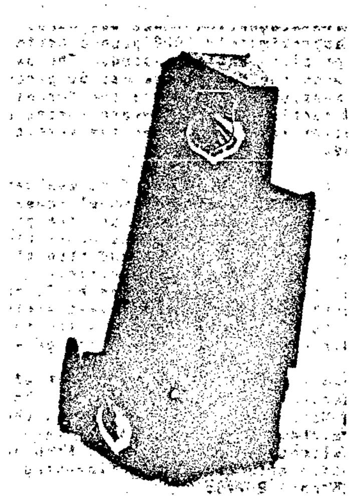

FIGURE 3. VENTED FLOW-STAGNATION PANELS

High pressure airflow was also introduced into the low-pressure regions surrounding the seat through porous fabric used in the construction of the flow-stagnation fence. In these configurations, the high energy airflow would be perpendicular to the general airflow surrounding the seat. The porous flow-stagnation fences would be simpler to manufacture and, theoretically, should transfer the high energy air more efficiently. However, the wind tunnel tests indicated that the porous fences increased the drag significantly and no further tests were done with these materials (8).

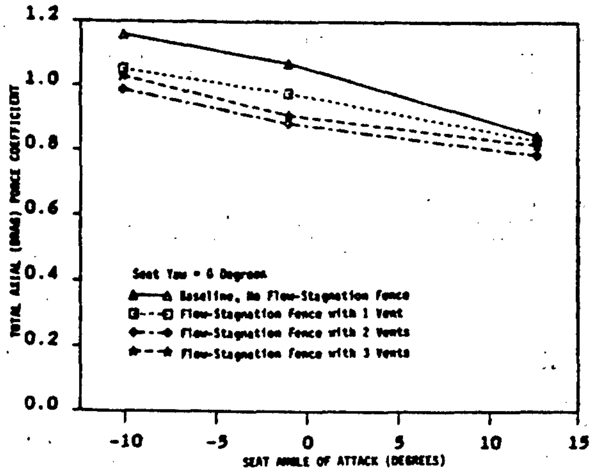

FIGURE 4. TOTAL SEAT DRAG VS. ANGLE OF ATTACK, VENTED CONFIGURATIONS

APPLICATION OF CONCEPT

The U.S. Air Force is currently conducting an advanced development program called the Crew Escape Technologies (CREST) Advanced Development Program under the direction of the Human Systems Division of the Air Force Systems Command. The objective of the CREST program is to develop and demonstrate, through full-scale testing, new escape technologies required to reduce fatalities and major injuries in future aircraft ejections. Extending the high-speed performance limits to 700 KEAS is a major goal of the program. Currently, the flow-stagnation concept is the windblast protection technology that is being demonstrated, along with other critical subsystems such as crew restraint, advanced propulsion and digital flight control. The Boeing Advanced Systems Company is the prime contractor responsible for the effort.

The CREST configuration for the flow-stagnation fence is significantly different than the designs tested previously (Figure 5). The fence design consists of an upper section made of high-strength Kevlar fabric attached to the seat back. This upper section forms a bonnet for the crewmember and acts as the flow-stagnation fence. The lower section on each side of the seat is made of net material designed to entrap the arms. The arm retention net consists of a triangular-shaped piece of material with a flexible cable routed through the leading edge of the entire fence. The aft edge of the arm retention net is attached to the seat sides. The arm retention net and deployment cable are stowed with the flow-stagnation bonnet. The assembly is deployed during ejection initiation with the bonnet and arm retention net being pulled into place tightly with the leading edge cable and cable-to-seat attachments. Deployment is powered with a linear actuator and capstan. For lower extremity restraint, the seat side structure is extended forward and fit with deployable metal panels that are designed to prevent foot rotation. When deployed, these panels are located on both sides of each foot. With this anti-rotation panel design, the legs must be raised to make sure the feet are

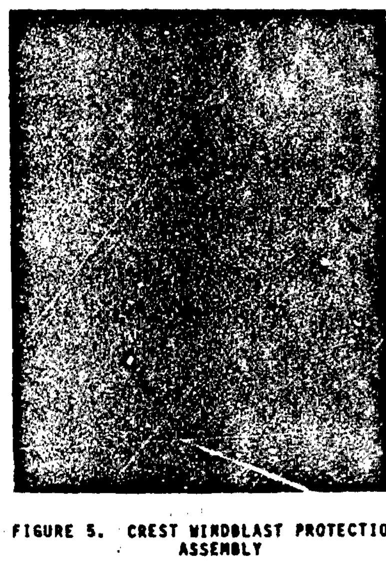

FIGURE 5. CREST WINDBLAST PROTECTION ASSEMBLY

positioned above the bottom edge of the panels. The foot panels are also deployed the instant the ejection handles are pulled. They are mechanically connected with a latching mechanism to the ejection handles. When the handles are pulled, the panels rotate and lock into place (9).

The CREST design requirements for the windblast assembly were that the lift loads acting on the head and neck would not exceed 300 pounds and the side loads would not exceed 50 pounds during a stabilized ejection trajectory. This applies throughout the escape envelope which includes ejections at dynamic pressures up to 1660 psf. Drag loads on the head were not specified since the aerodynamic and inertial loads were expected to be reacted through the headrest of the ejection seat. The design goals for the CREST windblast protection assembly were established using the probability of injury for various ejection airspeeds and wind tunnel data collected using scale models designed for measurement of the aerodynamic loads acting on various segments of the crewmember's body.

CREST WIND TUNNEL TESTS

Boeing conducted wind tunnel tests at the Arnold Engineering and Development Center to gather aerodynamic data on the crewmember and seat combination and to verify the design of the windblast assembly (10). The tests were conducted in two different tunnels: the 16 X 16 foot transonic tunnel and the 16 X 16 foot supersonic tunnel. In the transonic tunnel, the investigation was run at Mach numbers from 0.6 to 1.5 at angles of attack from -25 to 90 degrees and sideslip angles from -30 to +30 degrees. In the supersonic tunnel, the data were obtained at Mach numbers 2.0, 2.5 and 3.0 at angles of attack from -10 to 70 degrees and sideslip angles from 2 to -18 degrees. The dynamic pressure was varied from 135 to 400 psf and 117 to 250 psf in the transonic and supersonic tunnels, respectively.

The crewmember and ejection seat were one-half scale models that included sufficient detail to aerodynamically represent the geometry of the CREST seat configuration. However, the wind tunnel model was not equipped with anti-rotation foot panels located along the instep. Overall crewmember and seat forces and moments were measured by a six-component, internally-mounted balance. The crewmember was instrumented to measure the aerodynamic forces and moments acting on the crewmember's limbs plus static pressures located at various critical points on the manikin. Of specific interest were the aerodynamic drag loads acting on the seat as well as the side and lift loads acting on the crewmember's head.

The total forces and moments measured on the CREST seat with a windblast protection assembly were significantly different from those measured on the basic configuration not equipped with a windblast protection assembly. High axial-force (drag) and pitching-moment coefficients were measured. At the designed trim position of 30 degrees, the increase in magnitude of the axial-force and pitching-moment coefficients were approximately 60 and 150 percent, respectively, at a Mach number of 0.6. The magnitude of the axial-force coefficient as well as the normal-force coefficient increase with increasing Mach number up to approximately Mach 1.3 (as much as 0.4 for the axial-force coefficient). Above Mach 1.3, both force coefficients remain essentially constant with increasing Mach number. For typical open ejection seat configurations, the maximum axial- (drag) and normal- (lift) force coefficients are obtained at angles of attack at which the largest model-projected areas most closely align with the corresponding force directions. These are usually zero degrees for the axial-force coefficient and 90 degrees for the normal-force coefficient. However, with the CREST ejection seat configuration, the maximum axial-force coefficient occurred at an angle of attack of -20 degrees. The drag decrease with angle of attack is largely a result of the continual reduction in frontal area opposing the freestream velocity.

Of greater importance to the stability characteristics of the CREST seat design is the 100 percent increase in pitching-moment coefficient over the Mach number range from 0.6 to 3.0 in the vicinity of zero degrees angle of attack (Figure 6). Since a large portion of the moment changes occur at speeds above Mach 1.5, shock wave formations are a potential hazard. At the design trim angle of 30 degrees, however, the pitching-moment coefficient exhibits significant decreases with increasing Mach number. This pitching-moment characteristic means the control system inputs and propulsion could vary significantly depending on the initial conditions at the time of ejection initiation.

The lateral/directional (yaw, yawing-moment and rolling-moment) aerodynamic coefficients were sensitive to changes in yaw angle only slightly at low Mach numbers and negligibly at higher Mach numbers. The coefficients increased with increasing Mach number up to Mach 1.2. Above Mach 1.2, these coefficients generally decreased with increasing Mach number. The yaw and yawing-moment coefficient increased with increasing yaw angle. The rolling moment was nearly constant with yaw angle to approximately 10 degrees before increasing with further yaw angle increases.

The head loads measured were well within the windblast design requirements for the entire range of seat attitudes and Mach numbers tested. However, the forces acting on the head of the model in the fore and aft directions changed considerably with angle of attack (alpha) and Mach number. The magnitude of the force was measured to be approximately the same as what would be expected if no windblast protection assembly were added to the seat. However, the line of action of the force with the windblast protection assembly was in the opposite direction. Pressure data measured in the area of the head indicate stagnation pressures behind the head but less than stagnation pressures on the front of the head resulting in a net forward force. The largest variances were measured at zero and 40 degrees angle of attack for the lower and higher Mach numbers, respectively (Figure 7).

Serious head oscillations could occur as a result of these negative forces pulling the head forward off the headrest and away from the flow-stagnation bonnet. Once the head is pulled off the headrest, large positive pressures develop on the head and helmet combination and force it back into the bonnet and headrest. Once the head is back within the bonnet, the process is repeated (11).

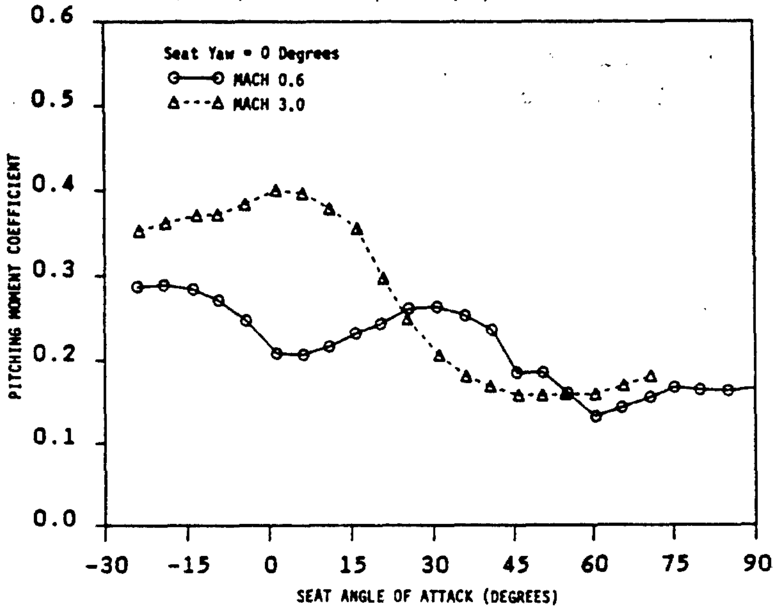

FIGURE 6. PITCHING MOMENT COEFFICIENT VS. ANGLE OF ATTACK

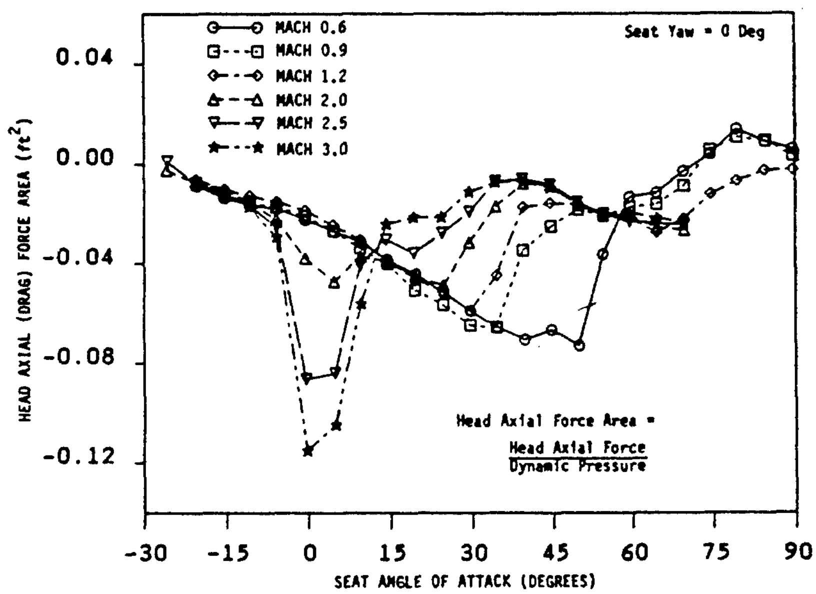

FIGURE 7a. HEAD AXIAL FORCE AREA VS. ANGLE OF ATTACK

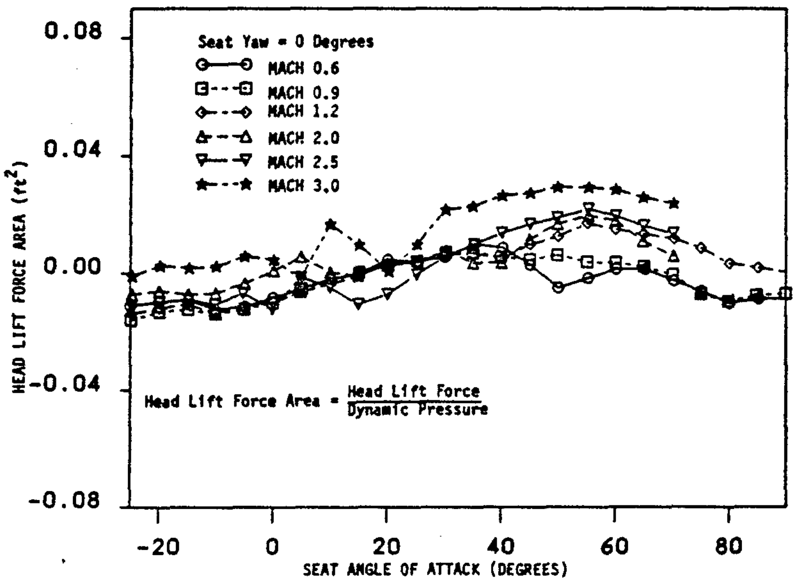

FIGURE 7b. HEAD LIFT FORCE AREA VS. ANGLE OF ATTACK

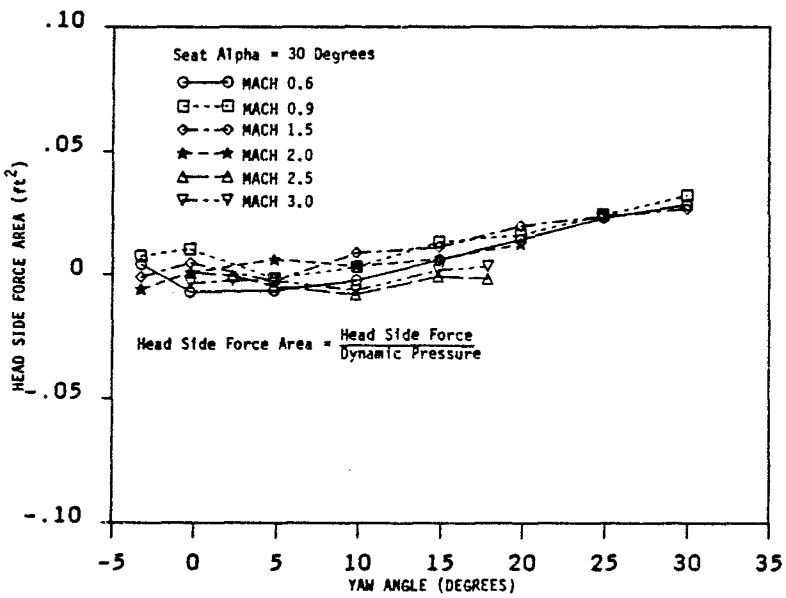

FIGURE 7c. HEAD SIDE FORCE AREA VS. YAW ANGLE

CREST WINDBLAST TESTS

Four windblast test series using the CREST windblast assembly were conducted by Boeing. The first and third series, accomplished at the Dayton T. Brown Windblast Test Facility, evaluated the structural integrity of the seat and windblast assembly and measured the aerodynamic loads acting on the manikin's head and neck. The second series was accomplished using the same test articles with the F-16A forebody for realistic flow simulation impinging the crewmember and seat. The fourth series was conducted at the Boeing Transonic Windblast Generator System. These windblast tests were conducted to demonstrate the efficacy of configuration changes to the seat structure and windblast assembly that were required after the first three test series. A forebody was not used for these tests.

The windblast assembly, manikin and seat that were tested varied slightly from the scale model tested in the wind tunnel. First, the model used in the wind tunnel was a half-scale 50th percentile crewmember and ejection seat. The exterior was made of smooth fiberglass, and clothing and flight gear were not simulated. For the windblast tests at Dayton T. Brown and Boeing, a full-scale manikin with flight gear was tested in a full-scale ejection seat. The seat was complete with the instep anti-rotation panels attached.

The tests that were conducted at Dayton T. Brown facility used a controlled release of stored, compressed air to simulate the windblast environment. The planned test speeds were 400, 500, 600 and 700 KEAS. A calibration run of 350 KEAS was conducted for instrumentation verification.

Significant failures plagued the first three series of tests and prevented any of them from reaching completion. Runs of 600 and 700 KEAS were made in the first series before instrumentation difficulties and structural inadequacies stopped the testing. The second series featured the F-16A forebody section with the seat placed in one of two locations. The first position tested was all the way into the cockpit; the test velocity was 600 KEAS, and no significant failures were observed. The second position was placed to represent the completion of the catapult stroke, approximately 40 inches above the previously tested location. In this position, the manikin and seat were impacted with the full blast of the 700 KEAS windstream. When the condensation fog cleared, the right and left sides of the seat bucket, including the foot anti-rotation panels to aft of the ejection handles, had been ripped away. Both legs were rotated 90 degrees outboard and were broken. The right leg was broken at the knee and the left leg was broken at the thigh. Testing was suspended until structural redesign could be accomplished.

Five tests were again planned for the next series of tests. Low speed runs of 350, 500 and 600 KEAS would be used to identify potential problem areas for the seat structure and to checkout the instrumentation prior to the 700 KEAS test. A 450 KEAS, 20 degree yaw test would be accomplished after the completion of the high-speed run. During the 500 and the 600 (620 actual) KEAS tests, the manikin's head rotated to the right approximately 70 to 80 degrees, and 10 degrees downward. Rotation was more pronounced during the 620 KEAS test. Head rotation was not observed during the 350 KEAS calibration run. The head rotation in the high-speed runs caused the head to partially leave the flow-stagnation bonnet. The manikin's oxygen mask and hose were pulled off the face of the manikin after the head rotated. This was not observed during the 500 KEAS test. Because of these observations, the last two runs were not attempted.

The final series was more successful. Runs of 600, 700 and 450 KEAS were completed. The 450 KEAS test was run at a yaw angle of 20 degrees; venting was added to the flow-stagnation bonnet to reduce the stagnation pressure region behind the head and thereby reduce the forward acting force on the head. The forces measured on the head during the 700 (750 actual) KEAS test are shown in Figure 8. No adverse effects were observed on the 450 KEAS test and there were no structural failures during this test series.

DISCUSSION AND CONCLUSIONS

The final evidence indicates that there may be hope for the crewmember trapped in George Smith's dilemma. Laboratory testing, both in concept feasibility studies and applications testing, shows potential for decreasing the aerodynamic loading occurring on the body segments of ejecting crewmembers. This should translate into reductions in windblast injuries. However, this reduction may be undermined to an unknown degree by changes in configuration or other alterations in the flowfield surrounding the crewmember.

In theory, once the crewmember's limbs are within the region of airflow stagnation, the large disparity between forces is eliminated. Reducing this in practice has been difficult to accomplish. The original model test data show the most effective seat attitudes for the concept are coincident with the maximum drag attitudes of the seat. These angles are not acceptable for a flying trim position because human deceleration tolerance would be exceeded and/or propellant requirements would be prohibitive. Trimming the seat at more extreme angles brings tolerance within acceptable boundaries but causes the stagnation areas within the fence to change such that forces now act to dislodge the limbs from the windblast protection assembly. This became evident during the CREST wind tunnel and windblast tests with the fore and aft force acting on the head. The flow-stagnation concept was also sensitive to configuration. The degree of protection and aerodynamic properties were changed significantly with changes in configuration. Aerodynamic drag was reduced when venting holes were added to fence design. Head loads were likewise lessened during CREST windblast tests.

The battle cry of the experimentalists is being shouted: more tests are required for completely successful implementation of the flow-stagnation concept. Forebody effects have yet to be defined. These effects include not only a flowfield that is possibly higher in magnitude but also one that is varying in direction. Also, no attempts have been made to quantify the aerodynamic coefficients of the ejection seat with the flow-stagnation fence as it emerges from the cockpit.

The flow-stagnation concept is a solution to windblast protection that is configuration dependent. If research and development is fully supportive, then flow-stagnation designs should closely resemble the configurations that are planned for eventual use. The CREST configuration was based on the requirements to limit the net forces acting on the head and to provide overall windblast protection for the crewmember. Although the design does not reflect that which was tested in the laboratory, it appears to have met the stated requirements and remains a simple, passive approach to providing windblast protection for advanced ejection seats.

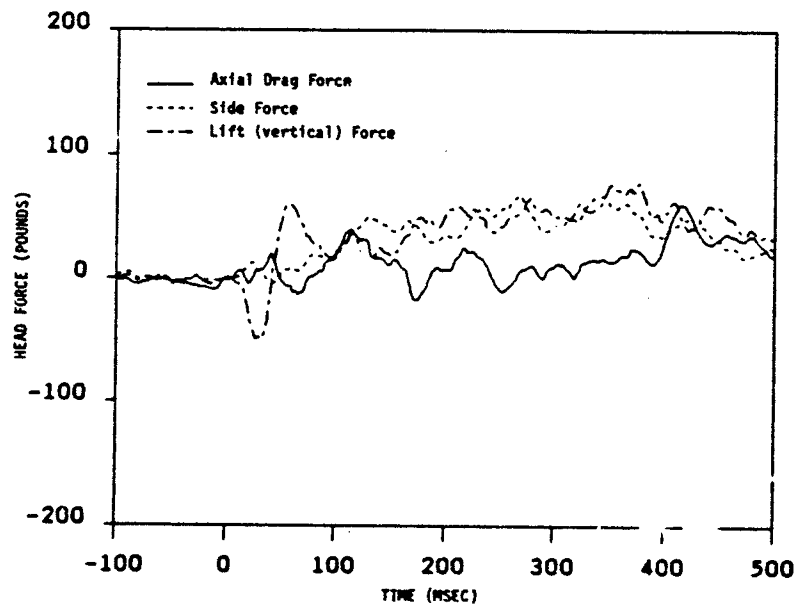

FIGURE 8. CREST WINDBLAST TEST SERIES IV HEAD LOADS

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CONTROLLABLE PROPULSION FOR ESCAPE SYSTEMS CONTROL

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SUMMARY

Current escape systems for military aircraft use solid-grain rockets for propulsion. These provide a fixed level of thrust for a fixed period of time. Since the escape system has to function over a wide range of conditions, this approach is a compromise. Significant improvements in escape capability could be achieved by introducing a propulsion system in which the thrust-time profile could be varied to suit the circumstances of each emergency. The technology now exists to introduce a fully controllable propulsion system. Such a system would not only provide a variable thrust-time profile but would also permit the propulsion system to provide stabilization, to control the forces applied to the crew member, and to control the escape trajectory. These capabilities would allow improved system operation throughout an expanded escape envelope. The technology for a fully controllable propulsion system has already been demonstrated in a development program.

INTRODUCTION

Douglas Aircraft Company, in conjunction with TRW Inc. and McDonnell Douglas Astronautics Company, has been working on the development of a controllable propulsion system for escape systems in military aircraft. This type of propulsion system has very significant implications for future expansion of aircrew escape envelopes and for additional capabilities that promise to enhance the probability of successful escape. Douglas has demonstrated the advanced technology needed to establish the feasibility of the approach.

DISCUSSION

Current escape systems use solid-grain sustainer rockets to propel the ejected crew member away from the aircraft. These rockets, by virtue of their design, deliver a fixed impulse every time they are used, regardless of the circumstances of the emergency. The characteristics of the sustainer rocket are therefore usually determined by the maximum impulse requirements. Typically, this would be the impulse required for tail clearance at high speed or for adequate height for the parachute to open in an ejection at zero altitude and zero speed. In other circumstances, this impulse can either be helpful — if the aircraft is level but sinking, close to the ground — or harmful, if the same aircraft happens to be inverted close to the ground.

In contrast, a controllable propulsion system can be varied to provide the thrust-time profile which is desirable for a particular set of emergency circumstances, and it can also be used to perform a range of other tasks that enhance and expand the capability of the system. For instance, the system might be used to stabilize the seat and crew member; control acceleration, thrust vector, and the trajectory; and shape the trajectory to avoid the ground.

The controllable propulsion system with the potential to perform these tasks is composed of the sensor, controller, and propulsion subsystems.

Propulsion subsystem technology that is acceptable for escape systems has proven difficult to acquire. Controllable propulsion systems have existed for many years, a prime example being the system which enabled the Lunar Lander to make a controlled descent to the surface of the moon. However, this feat was achieved using liquid propellant rockets, which have not been seriously considered for escape systems for safety reasons. The controllable propulsion system that is fully compatible with an escape system was made possible by the development of gelled propellants.

GELLED PROPELLANTS

Gelled propellants, as the name implies, are liquid propellants that have been transformed into gels. In the gelled form, these propellants retain the operational characteristics of liquid propellants but their characteristics with regard to safety and handling are equal or superior to those of solid-grain propellants.

The gelled fuel and gelled oxidizer are vital to the operation of the controllable propulsion system because they are thixotropic (i.e., solids that liquefy when a shear force is applied) and hypergolic (i.e., materials that combust spontaneously when mixed together).

In a propulsion system, the gelled propellants are pressure-fed through valves into the combustion chamber of a rocket engine, where they spontaneously ignite and generate thrust. These engines, like their liquid propellant counterparts, have two operational features that make them ideal for use in a controllable propulsion system. First, the valves can be turned on and off to control the flow of the propellants, and therefore the thrust. Second, the valves can be designed to control the flow of the propellants and thus vary the thrust down to a small fraction of the full-flow value. Another important feature is that the control valves can operate very rapidly. For example, the engine that has been designed and tested in the Douglas program can be turned on, the thrust increased to 90 percent of maximum, and the engine turned off again — all in an elapsed time of 8 milliseconds.

PROPULSION SUBSYSTEM

The controllable propulsion subsystem basically provides thrust to propel the crew member away from the aircraft and provides moments to control seat attitude. If the subsystem can perform these two tasks simultaneously and can be turned on and off, then, given sufficient thrust and impulse, it can also provide a trajectory that will clear the tail of the aircraft, avoid other crew members, and help to avoid premature contact with the ground; keep the forces on the crew member within selected human tolerance limits; provide a thrust-time profile tailored to the ejection conditions, and perhaps fulfill other requirements. A simple schematic of a propulsion subsystem that can perform these tasks is shown in Figure 1. In this system, a gas generator forces gelled fuel and oxidizer from storage tanks to four engines. The flow of fuel and oxidizer to each engine is controlled by valves mounted on the individual engines. When the four engines are arranged on an ejection seat so that their thrust vectors are offset from the center of gravity, as shown in Figure 2, then the overall thrust and rotational moments in pitch and yaw can be controlled simply by controlling the relative thrust of each engine. Roll moments can also be handled by skewing the thrust vectors or by adding more engines. However, roll control is essential only for the most ambitious requirements such as ground avoidance.

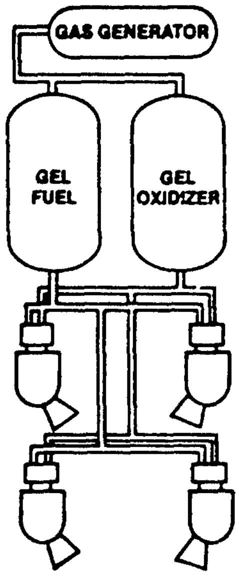

Figure 1. Propulsion Subsystem Schematic

CONTROLLABLE PROPULSION SYSTEM

The controllable propulsion system consists of three subsystems: sensors, avionics, and propulsion. Although the capabilities of a controllable propulsion system may vary widely, they are primarily a function of the sensors and, to a lesser degree, of the avionics. It appears that the propulsion subsystem should operate in essentially the same manner regardless of the overall system design. It is therefore convenient to describe the operation of the controllable propulsion system by reference to the role it would play in a high-speed escape.

In an ejection, a catapult will provide the initial movement up the cockpit guiderails and the controllable propulsion system will take over following catapult separation. As the seat emerges from the cockpit and becomes a free body, the microprocessor, as shown in Figure 3, will use the sensor data to generate commands to each of the engines. These commands are based on computations of trajectories and forces and are selected to achieve a satisfactory trajectory using forces which are within the appropriate human tolerance limits.

A most important factor in the computational process is seat attitude since this affects the thrust vector, the magnitude of the aerodynamic coefficients, and the direction of the aerodynamic forces on the crew member.

Another factor is the selection of priorities. Since all four engines are playing a part in simultaneously controlling the total thrust, the thrust vector, the yaw moment, and the pitch moment, the available thrust of each engine must be allocated to the tasks in proportion to their importance in the overall success of the escape. Our experience indicates that yaw control usually rates the highest priority, with pitch control a close second.

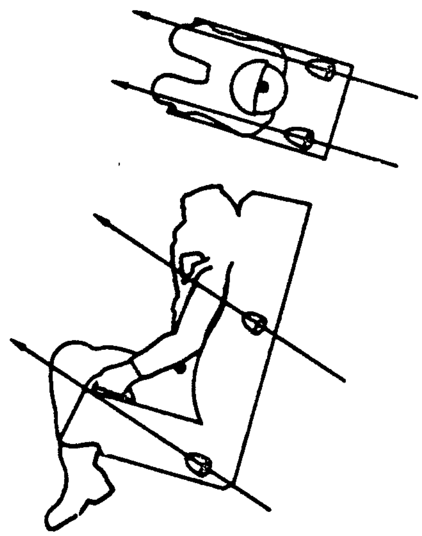

Figure 2. Rocket Engine Arrangement

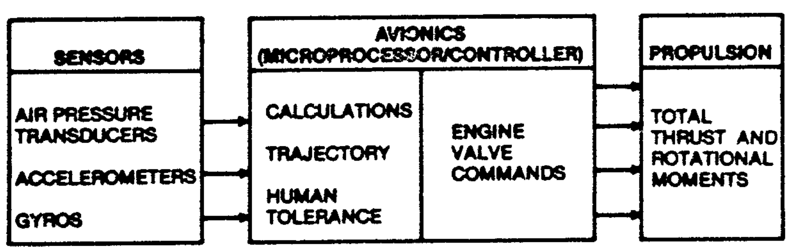

Figure 3. Schematic of Controllable Propulsion System

In an ejection at very high speed, the aerodynamic forces are also very high, and angular motion of the seat must be controlled if tumbling is to be avoided. The cycle time between sensing and applying the selected engine settings should therefore be short enough to maintain stability without violent oscillations. In the system we have developed, the engine commands are updated every 10 milliseconds.

There are two ways in which the engine can be designed to respond to a thrust command. For example, if, for one of the 10-millisecond control periods, the microprocessor requires an engine to produce half of its full thrust, the engine could either be turned on full thrust for 5 milliseconds or be throttled at half thrust for 10 milliseconds. The engine design we have demonstrated uses the on-off approach.

The operation of a controllable propulsion system in an escape at 800 keas is illustrated in Figures 4 through 6. Figure 4 shows a sequence of engine thrust commands together with the actual thrust profile for one engine over a 120-millisecond period. The performance of the system relative to the selected human tolerance limits is illustrated in Figure 5. The risk levels shown on this plot are approximations of the levels derived from Brinkley.*

An ejection from an aircraft at 800 keas is considered a "high risk" situation and therefore the plot indicates that the forces imposed on the crew member were satisfactorily below the limit during this period.

Figure 6 shows the seat trajectory relative to the aircraft and illustrates the changing engine thrust levels.

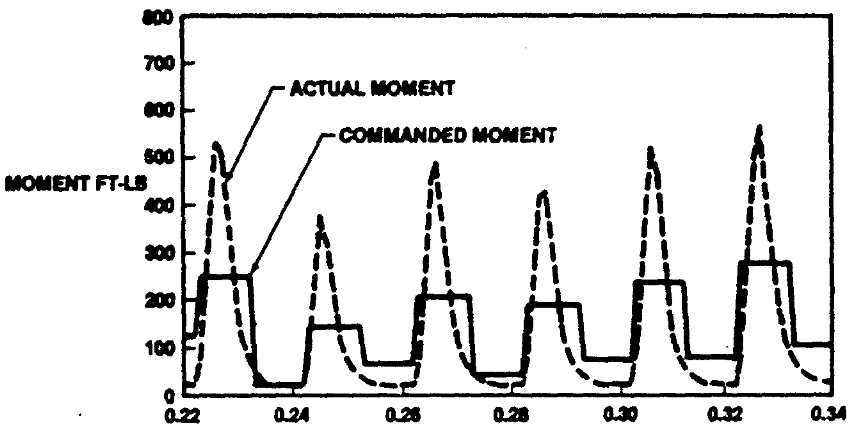

Figure 4. Moment Commands Versus Actuals

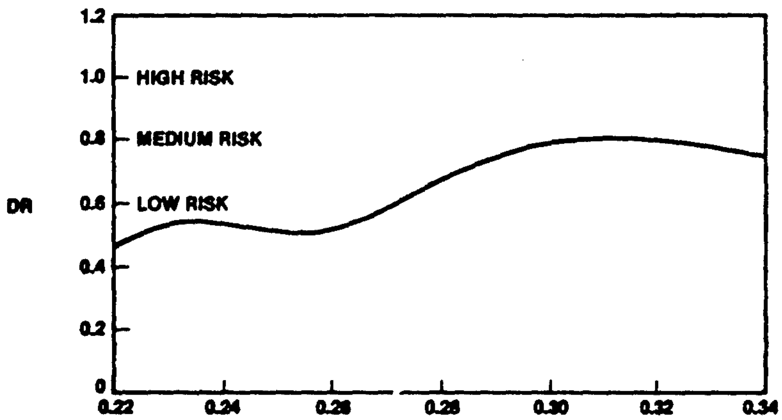

Figure 5. Dynamic Response Radical

CONTROLLABLE PROPULSION – GROWTH CAPABILITIES

A controllable propulsion system will permit the escape system to provide capabilities that are difficult to achieve with conventional propulsion systems. The most important of these are "upward seeking" and "threat assessment" features. Both of these concepts have significant implications for future escape systems.

Upward Seeking

With upward seeking features, the controllable propulsion system is used to achieve a trajectory in which the seat and occupant are steered upward so that they are away from the ground. In order to execute an upward seeking, or ground avoidance, maneuver, the propulsion controller needs to know in which direction the ground lies. Also, if this capability is reserved for use when the ground is so near that it could be life-threatening, then the controller will need to know how far away the ground is and whether or not the seat is traveling toward it. Although some of this information may be difficult to acquire, none of the problems appear to be insurmountable.

The use of the propulsion system to reverse the downward motion of the seat has the potential, as illustrated in Figure 7, of achieving dramatic improvements in performance under high-sink-rate or dive conditions.

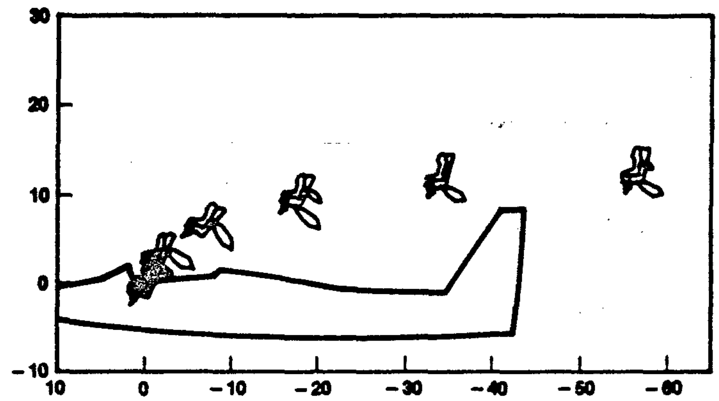

Figure 6. Trajectory and Engine Operation

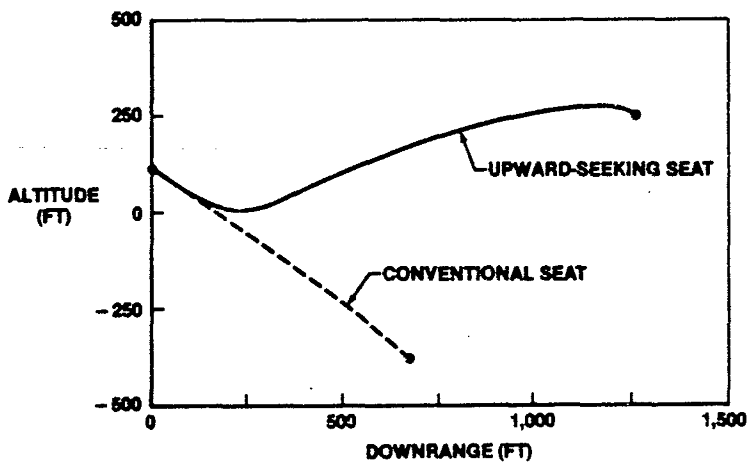

Figure 7. Performance Comparison At 300 KEAS 30-Degree Dive

Although an upward seeking system could be effective throughout the speed range, the impulse required to reverse the direction of motion becomes prohibitive at high downward speeds. However, as most low-altitude escapes are in the low-speed portion of the envelope, the upward seeking approach could significantly reduce the number of unsuccessful "out-of-the-envelope" escapes.

Threat Assessment

In current escape systems, the acceleration forces on the crew member are allowed to be relatively high because this may save his life. However, they must not be so high that they produce an unacceptable incidence of ejection injuries. In a system with a "threat assessment" capability, the system would use sensors to provide information on the magnitude of the threat to the crew member's life. Once this has been established, the system would control the forces imposed on the crew member, including the propulsion forces, in relation to the threat.

A threat assessment capability therefore has the potential for achieving both an increase in the success rate and a reduction in the incidence of unwarranted ejection injuries.

STATUS

In the Douglas controllable propulsion program, a demonstration propulsion subsystem has been designed and tested. This effort included development testing of the gas generator and gel propellant engines. The component tests were followed by the successful test firing of a complete propulsion subsystem in which four engines performed a high-speed ejection duty cycle.

OTHER ESCAPE SYSTEM APPLICATIONS

In the preceding text, the controllable propulsion system has been linked to "escape systems." Although only ejection seats were specifically identified, it is apparent that capsule escape systems would also benefit from the use of a controllable propulsion system. Also, a controllable propulsion system in a capsule would provide the option of reactivating the propulsion system to reduce the forces associated with ground impact.

CONCLUSIONS

Development of the key rocket propellant and engine technology should enable a controllable propulsion system to be introduced to replace solid-grain systems in future escape systems. This development could result in a major improvement in future escape system capability at high speeds, and at low altitudes, and in a reduced probability of ejection injuries throughout the entire escape envelope.

EXIGENCES DU SCAPHANDRE DE PROTECTION DE L'EQUIPAGE D'HERMES

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RESUME

Dans sa configuration actuelle, l'avion spatial HERMES est équipé d'une capsule éjectable pressurisée destinée à assurer la sauvegarde de l'équipage au cours des phases critiques du lancement et de la rentrée atmosphérique. Capable d'opérer dans un domaine très vaste (jusqu'à M = 7, Z = 60 km) imposé par les performances du lanceur, la capsule procure à l'équipage de 3 spationautes les protections physiologiques nécessaires depuis l'éjection jusqu'à l'atterrissage ou l'amerrissage. Cependant, la perte de pressurisation accidentelle de la cabine d'HERMES reste un évènement redouté qui ne peut être écarté, ce qui impose à l'équipage le port préventif de scaphandres de protection individuelle. Déduites de l'analyse des missions et des évènements redoutés, les fonctions du scaphandre sont décrites et justifiées par les limitations physiologiques qu'elles compensent et par les contraintes opérationnelles rencontrées. Reste l'intégration du système scaphandre dans l'avion spatial : cela concerne aussi bien l'intégration physique avec la détermination des interfaces que l'insertion des procédures d'utilisation dans les scénarios de mission nominaux et de secours.

INTRODUCTION

Les informations contenues dans cet article sont issues d'une étude réalisée pour le compte de l'Agence Spatiale Européenne avec la collaboration de la société DORNIER, et d'une étude préliminaire effectuée pour le CNES.

Dans sa définition actuelle, l'avion spatial HERMES, mis en orbite par le lanceur ARIANE 5, a pour principale mission d'emmener un équipage de 3 spationautes, de s'accoster à un module orbital pour en effectuer la desserte puis d'exécuter une rentrée atmosphérique non propulsée terminée par un atterrissage horizontal. Bien que la phase d'étude, actuellement en cours, conduise à un grand nombre de configurations potentielles, les éléments déterminants pour la sécurité et la sauvegarde de l'équipage sont à peu près connus, puisque déterminés par les performances du lanceur, les trajectoires de lancement et de rentrée. L'analyse des risques encourus au cours des phases atmosphériques a permis de conclure à la nécessité d'un système de sauvetage, comme en disposent d'ailleurs les programmes analogues, et ce particulièrement depuis l'accident de Challenger.

Pour être efficace, le système de sauvetage doit couvrir un domaine de vol suffisant, tout en garantissant sa crédibilité, et ceci dans un contexte de très fortes contraintes sur les masses. Le compromis retenu à ce jour consiste à couvrir la totalité de la phase la plus critique : la période de fonctionnement des propulseurs à poudre au cours du lancement. Pour y parvenir la solution ambitieuse d'une cabine éjectable pressurisée a été choisie pour l'avion de référence malgré un évident handicap de masse. Ceci représente un défi technologique majeur en raison de l'étendue du domaine d'éjection (M = 7, Z = 60 km).

Etant donné que la perte de pressurisation accidentelle de la cabine est un évènement catastrophique qui ne peut être rejeté, survenant notamment au cours de la séquence d'éjection, la survie de l'équipage passe par une protection physiologique individuelle assurant le maintien de la pression et la fourniture d'atmosphère respirable : d'où un scaphandre conçu comme un équipement de secours ultime. Dans la recherche d'un autre compromis masse/domaine de sauvetage, d'autres démarches visent un gain de masse système en répartissant les fonctions de sauvetage entre un scaphandre d'une part pour toutes les fonctions de support-vie et un système allégé d'autre part pour les seules fonctions d'éjection.

Le port d'un scaphandre de protection individuelle s'impose donc, soit dans la capsule éjectable de référence dont il contribue à asseoir la crédibilité, soit dans un système d'éjection allégé dont il constitue un élément vital.

Compte tenu des circonstances et du domaine d'éjection considérés, le scaphandre doit être porté préventivement par l'équipage de manière à être instantanément opérationnel en cas de nécessité. Ainsi donc, aux fonctions de survie dimensionnées par les conditions de secours viennent s'ajouter des fonctions dont le but est d'autoriser l'usage du scaphandre dans des conditions de vol nominales tout en minimisant les contraintes d'intégration dans le poste de pilotage. Les exigences fondamentales du scaphandre sont exprimées en termes de fonctions de contrôle d'environnement et support-vie, d'ergonomie, d'information et communications. Egalement liées au port systématique du scaphandre lors des phases critiques, certaines fonctions, dites intégrées, sont mentionnées d'une part à cause de la simultanéité de leur nécessité avec celle du scaphandre, d'autre part parce que le scaphandre constitue un support d'intégration judicieux.

Enfin, les contraintes d'intégration spécifiques à l'avion spatial HERMES, sont considérées comme préalables aux choix de solutions techniques capables d'assurer les fonctions mentionnées plus haut. Ces contraintes sont de deux ordres, les interfaces avec l'avion et les procédures d'utilisation. Là encore un compromis est à trouver, propre à chaque configuration de véhicule et profil de mission, entre la part d'intervention humaine, de procédures, et la part d'actions automatiques réalisées par le système scaphandre et ses interfaces avec le véhicule.

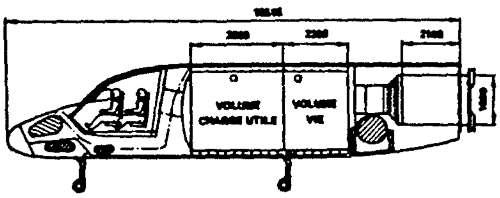
CONFIGURATION D'HERMES

Description générale

En dépit de différences entre configurations possibles dont la figure 1 illustre un exemple, l'avion spatial HERMES comprend trois volumes pressurisés communs aux diverses versions.

- La capsule éjectable constitue le poste de pilotage d'HERMES où les trois membres d'équipage sont installés lors des phases de lancement et de rentrée. L'aménagement général de la capsule est présenté sur la figure 2 (Réf.2). Il comprend les trois sièges, les commandes de pilotage d'HERMES, des équipements de support-vie et d'avionique et tous les équipements liés à la sauvegarde de l'équipage. La capsule permet après éjection d'assurer une décélération avant l'impact, les fonctions de protection et d'atténuation des chocs, la survie pendant 24 h, la flottabilité, la signalisation radio et les communications.
- Le volume central est composé du volume destiné à la charge utile et du volume vie où sont situés les différents composants du système de support-vie et de contrôle de l'environnement (ECLSS) ainsi que des équipements d'avionique.
- Le sas sert à l'accès à une station spatiale lorsque HERMES est accosté et aux sorties dans l'espace. Lorsqu'ils ne sont pas utilisés, les scaphandres de sortie extra-véhiculaires (EVA) y sont stockés.

Les communications entre les volumes pressurisés s'effectuent par des passages étroits (diamètre 800 mm) pouvant être obturés afin de les isoler. L'accès à HERMES pour le lancement et l'évacuation au sol sont prévus au niveau du poste de pilotage par une ouverture de 800 mm de diamètre.



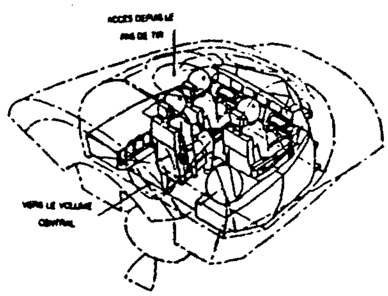


Figure 1 : Exemple de configuration d'HERMES   Figure 2 : Aménagement général de la capsule

Fourniture d'atmosphère/contrôle des pressions et conditionnement de l'atmosphère

La fourniture d'atmosphère et le contrôle des pressions ainsi que le conditionnement de l'atmosphère font partie de l'ECLSS. Ils assurent le maintien dans HERMES d'une ambiance respirable et climatisée similaire aux conditions terrestres : pression totale de 1013 hPa, taux d'oxygène de 21 %, température de 20 à 30°C, humidité relative de 40 à 60 %. Les principales fonctions sont données ci-après.

Le sous-système de fourniture d'atmosphère et de contrôle des pressions permet la fourniture d'oxygène et d'azote pour compenser la consommation métabolique d'oxygène de l'équipage et les pertes d'atmosphère (fuites structurales, opérations du sas), il assure la régulation des pressions totale et partielle d'oxygène. L'alimentation en oxygène des équipements individuels est prévue. En cas de nécessité, les volumes pressurisés d'HERMES peuvent être dépressurisés et/ou repressurisés. En cas de perforation de la cabine ou défaillance d'un joint, une provision d'oxygène et d'azote autorise une pressurisation de secours à 700 hPa (compensation pendant 6 heures d'une fuite par un trou de diamètre équivalent à 4 mm).

Le sous-système de conditionnement de l'atmosphère permet le maintien d'une ambiance du type "bras de chemise". Ses principales fonctions sont la régulation de la température et contrôle de l'humidité, la ventilation et circulation de l'air, la régénération de l'atmosphère (élimination de CO_2, de CO, des contaminants, des poussières, des débris et des odeurs). Du fait de la ventilation, une contamination de l'un des volumes d'HERMES se propagerait dans toute la zone pressurisée d'HERMES. Le retour à des conditions saines exigerait donc une purge complète du véhicule par dépressurisation suivie d'une repressurisation par du gaz propre.

ANALYSE DES MISSIONS

Une mission type d'HERMES se décompose en 4 phases principales :

- Préparation au lancement
- Lancement : fonctionnement des propulseurs à poudre jusqu'à t = 120 s
propulsion par l'étage cryogénique seul jusqu'à t = 600 s
insertion en orbite
- Phase orbitale
- Rentrée : vol atmosphérique (durée : 35 minutes)
approche finale et atterrissage (durée : 5 minutes)

HERMES assure la sécurité de l'équipage grâce à la protection combinée de l'avion spatial lui-même, de la capsule et des redondances de l'ECLSS. Les mesures prises pour la sauvegarde de l'équipage - mesures préventives, interruption de la mission, rentrée de secours et/ou éjection de la capsule - et les conditions opératoires associées pour faire face aux évènements redoutés durant les différentes phases de la mission sont rassemblées dans les tableaux 1 à 4. Une décompression de la cabine d'HERMES peut être temporairement compensée par l'ECLSS, selon l'importance de la fuite.

EVENEMENTS REDOUTES	POSSIBILITES D'EVACUATION AVANT LE LANCEMENT	CONDITIONS ASSOCIEES
Anomalies de fonctionnement, incendie, foudroiement, explosion	Evacuation individuelle si la menace permet un temps de réaction long Toboggan (ou équivalent), équipage sauf en 60 s Ejection de la capsule si le sauvetage de l'équipage impose une réaction immédiate	Ambiance éventuellement contaminée Températures extrêmes : boule de feu Atterrissage de la capsule dans un périmètre de 1 à 4 km

Tableau 1

PHASES	POSSIBILITES DE SAUVETAGE LORS DU LANCEMENT	CONDITIONS ASSOCIEES
Propulsion par propulseurs à poudre $t < 120$ s $M < 7$ Altitude < 60 km	Ejection de la capsule. La décision d'éjection instantanée pourra être prise à l'insu de l'équipage	• Atterrissage dans un périmètre de 1 km ou plus autour du pas de tir Contamination éventuelle • Amerrissage à proximité des côtes guyanaises. Récupération rapide de l'équipage (influence des conditions météorologiques et de l'état de la mer).
Après séparation des propulseurs à poudre $120 \text{ s} < t < 600 \text{ s}$	• Séparation de l'avion spatial et du lanceur puis stabilisation de HERMES. • Ejection de la capsule après retour dans le domaine d'éjection (opérations contrôlées par l'équipage, avec support du sol).	Facteur de charge (jusque 5,2 g) Amerrissage dans l'océan Atlantique. Récupération de l'équipage dans les 24 heures (influence des conditions météorologiques et de l'état de la mer)
Insertion en orbite	• Séparation de l'avion spatial et du lanceur. Vol vers un site transatlantique et/ou éjection de la capsule après retour dans le domaine • Si altitude et vitesse suffisantes : insertion en orbite, puis rentrée vers un terrain de secours (opérations contrôlées par l'équipage avec support du sol).	Amerrissage de la capsule dans l'Océan Atlantique (voir ci-dessus).

Tableau 2

EVENEMENTS REDOUTES	MESURES DE SAUVEGARDE ENVISAGEABLES EN ORBITE
Contamination de la cabine Feu	Utilisation des extincteurs et/ou purge volontaire puis repressurisation de tout le véhicule. La propagation d'une contamination à l'ensemble des volumes pressurisés sera inévitable du fait de l'efficacité de la ventilation. (Mise en oeuvre rapide d'une protection respiratoire)
Dépressurisation accidentelle de la cabine (défaillance d'un joint, perforation par débris ou micrométéorite).	Compensation par l'ECLSS et rentrée d'urgence dans un délai maximal de 3 à 6 heures. Le temps de réaction de l'équipage dépend de l'importance de la fuite
Défaillance d'un sous-système (panne double ou triple).	Rentrée d'urgence dans un délai maximal de 3 à 6 heures.
Eruption solaire	Cette protection n'est pas du ressort d'un équipement individuel.

Tableau 3

PHASES	POSSIBILITES DE SAUVETAGE LORS DE LA RENTREE	CONDITIONS ASSOCIEES
Désorbitation Rentrée jusque Mach 7	Aucune en cas de perte de contrôle de HERMES	
Rentrée après Mach 7 Phase finale et atterrissage	Séparation de la capsule	Atterrissage ou amerrissage Récupération de l'équipage dans les 24 heures (influence des conditions météorologiques et/ou de l'état de la mer).

Tableau 4

Malgré la protection apportée par HERMES, la capsule et les redondances de l'ECLSS, il s'avère que des situations dangereuses pour la vie de l'équipage ne peuvent être écartées (voir tableau 5). Les trois premières situations citées dans ce tableau conduisant à la perte de la pression totale exigent la présence à bord d'HERMES d'un scaphandre.

PERTE DE LA PRESSION TOTALE
• De la capsule durant son éjection • De la cabine de façon accidentelle durant le lancement, la rentrée ou en orbite • Du véhicule par purge volontaire après une contamination ou un feu
CONTAMINATION DE L'ATMOSPHERE
• Au sol lors d'une évacuation du pas de tir • Durant/après un feu, une défaillance ayant entraîné un dégagement de substances toxiques en cabine ou une utilisation massive des extincteurs
FACTEUR DE CHARGE / READAPTATION CARDIOVASCULAIRE
• Durant une séparation d'urgence d'HERMES et du lanceur • Évacuation d'urgence après l'atterrissage et un séjour en orbite
RECUPERATION DE L'EQUIPAGE ET SAUVETAGE EN MER
• Après éjection de la capsule

Tableau 5 : Situations dangereuses pour la vie de l'équipage

L'orientation possible du système de sauvetage d'HERMES vers des systèmes ouverts, ou partiellement encapsulés, rend plus indispensable encore la protection de l'équipage par un scaphandre (Réf.3, 4). La perte de pression est potentielle lors de l'éjection de la capsule, elle est une caractéristique du système lors du sauvetage par siège éjectable ouvert. Des contraintes supplémentaires sont également introduites par ce type de système d'éjection. Ce sont les contraintes usuelles d'éjection qui nécessitent la protection contre l'effet de souffle, les chocs, l'immersion dans l'eau ainsi qu'un dispositif de flottabilité individuel, la protection thermique nécessaire pour les éjections à grande vitesse pouvant être réalisée au niveau du siège (bouclier thermique).

LIMITATIONS PHYSIOLOGIQUES - FONCTIONS DU SCAPHANDRE

Outre les fonctions de bases, des fonctions qualifiées d'intégrées peuvent être assurées par le scaphandre avec le souci de réaliser un équipement de protection simple, léger, complet et d'emploi aisé. Sont rassemblées sous le terme de fonctions intégrées, les fonctions de protection liées aux opérations d'HERMES ou induites par le port du scaphandre et les contraintes d'interfaces avec HERMES. L'ensemble des fonctions à assurer par le scaphandre est présenté dans le tableau 6. L'analyse des exigences associées à ces fonctions est résumée ci-après.

CIRCONSTANCES	FONCTIONS REQUISES
Perte de pression de la capsule lors de sa séparation	FONCTIONS DE PROTECTION DE BASE
Fuite de la cabine ou perforation	
Contamination de la cabine ou feu	Maintien de la pression totale
Evacuation du pas de tir en ambiance contaminée	Fourniture d'une atmosphère respirable
	FONCTIONS INTEGREES
Lors du port du scaphandre	Contrôle thermique
Lors du port du scaphandre	Mobilité, dextérité
Fuite de la cabine ou contamination en orbite	Habillage/deshabillage en orbite
Lors du port du scaphandre	Vision
Séparation de secours entre le lanceur et l'avion spatial	Protection anti-g
Réadaptation cardio-vasculaire après l'atterrissage	Protection anti-g
Lors du port du scaphandre	Information et communications
Lancement et rentrée	Atténuation du bruit
Lors du port du scaphandre	Collecte de l'urine
Lors du port du scaphandre	Fourniture de boisson
Survie pendant 24 heures - Sauvetage en mer	Aide à la survie - Flottabilité - Harnais

Tableau 6 : Fonctions de protection

Fonctions de base

Maintien de la pression totale

Si l'on considère seulement le risque de perte de pression de la capsule lors de son éjection de l'avion spatial, la durée pendant laquelle le scaphandre doit assurer les fonctions de base est relativement courte (de l'ordre de 10 minutes). La protection offerte par un vêtement à contre-pression par vessie pressurisée (appelé "partial pressure suit") serait alors suffisante pour ces durées. En revanche, à la suite d'une dépressurisation de la cabine non compensable totalement par l'ECLSS, la protection offerte par un tel équipement n'est pas compatible avec la durée requise pour le retour sur Terre (de 3 à 6 heures). Un scaphandre à pression totale ("full pressure suit") est donc nécessaire pour couvrir ce cas.

L'ambiance d'HERMES étant à une pression de 1013 hPa et composée d'une atmosphère comprenant 79 % d'azote, des risques d'aéroembolisme apparaissent lorsque l'ECLSS n'est plus en mesure d'assurer une pression totale suffisante.

La pression minimale du scaphandre assurant la protection contre l'aéroembolisme est définie par le facteur R, défini par le rapport de la pression partielle d'azote dans les tissus avant la décompression à la pression du scaphandre (oxygène pur). Pour les opérations d'activité extravéhiculaire en scaphandre, la NASA considère que R = 1.22 constitue une valeur sûre, R = 1.4 est la limite pour les conditions nominales et R = 1.8 est envisageable pour des opérations d'urgence pour une durée inférieure à 30 minutes. Des valeurs de R supérieures à 2 sont supportées par les pilotes d'avions de combat sans symptômes graves. L'utilisation d'un scaphandre de protection dans HERMES représente une situation intermédiaire entre le cas de l'EVA et celui du pilote d'avion de combat tant du point de vue de la durée que du travail physique. Un facteur R de 1.8 peut donc être envisagé pour la protection de secours de l'équipage d'HERMES. Du fait du caractère imprévu des décompressions de la capsule ou de la cabine, la dénitrogénation qui permettrait de réduire les risques d'aéroembolisme n'est pas possible.

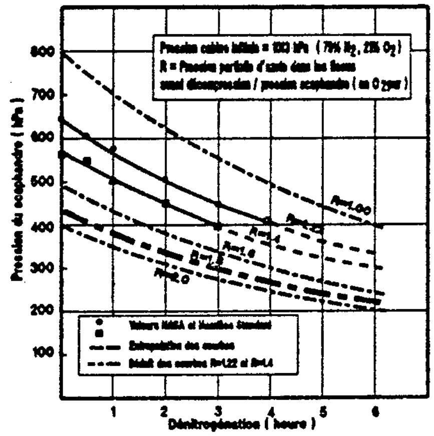


Figure 4 : risques d'aéroembolisme

La figure 4 donne, statistiquement, les risques d'apparition des symptômes d'aéroembolisme corrélés au facteur R, en fonction de la pression régnant dans le scaphandre (oxygène pur) et de la durée de la dénitrogénation. Pour l'application à la sauvegarde de l'équipage d'HERMES, ceci conduit avec R = 1.8 et sans dénitrogénation à une pression minimale dans le scaphandre de 450 hPa.

Fourniture d'atmosphère

En cas de décompression de la cabine ou de la capsule, une atmosphère respirable doit également être maintenue dans le scaphandre. La figure 5 schématise l'évolution des conditions respiratoires lors d'une décompression à partir de 1013 hPa (21 % d'oxygène) et la transition vers l'atmosphère d'oxygène pur du scaphandre pour éviter l'hypoxie. Ainsi, l'alimentation en oxygène pur du scaphandre prend automatiquement le relais de l'alimentation en air de la cabine dès que la pression de la cabine chute en-deçà de 650 hPa, cette valeur n'étant acceptable que de façon transitoire, quelques minutes au plus. La pression partielle de CO2 dans le scaphandre doit être limitée : 10 hPa en conditions normales et 20 hPa en conditions dégradées.

De plus, l'alimentation du scaphandre permet la fourniture d'un gaz respirable lorsque l'ambiance cabine est contaminée ou lorsque la pression partielle d'oxygène est trop basse. Ce dernier cas peut être géré par des procédures grâce à une alarme donnée par l'ECLSS (en fonction des pressions totale et partielle d'oxygène).

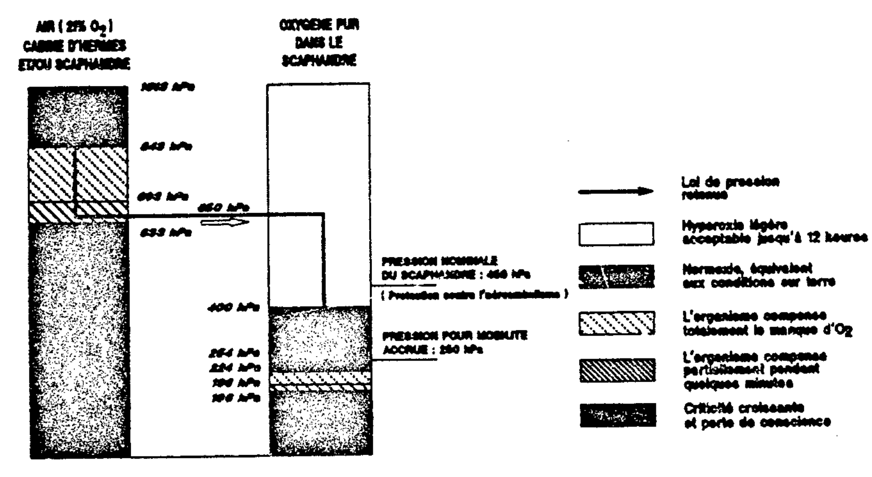


Figure 5 : Evolution des conditions respiratoires lors d'une décompression de la cabine

Fonctions intégrées

Contrôle thermique

Le port du scaphandre impose à l'équipage une contrainte thermique accrue. Afin d'assurer le confort thermique et le maintien des performances des spationautes, une climatisation est nécessaire. Les options concernant cette réfrigération dépendent de l'activité métabolique de l'équipage, de la durée considérée et du niveau de confort thermique requis.

Durant les phases nominales du lancement ou de la rentrée (équipage assis, activité métabolique inférieure à 180 W) un contrôle thermique efficace est nécessaire, c'est-à-dire que l'évacuation de chaleur ne doit pas entraîner une transpiration importante (évaporation cutanée de l'ordre de 50 à 200 g/h).

Un contrôle thermique moins performant est acceptable pour des conditions de secours telles que le retour d'urgence après une dépressurisation de la cabine ou une contamination (durée de 3 à 6 heures, activité métabolique inférieure à 180 W) ainsi que la purge de la cabine. Dans ces cas, l'évacuation de la chaleur métabolique repose sur une évaporation cutanée importante (supérieure à 200 g/h). Le bilan thermique est néanmoins équilibré.

Un contrôle thermique minimal est envisageable pour la descente de la capsule après séparation, phase de courte durée - 10 minutes - pendant laquelle l'équipage n'a qu'un rôle passif - activité métabolique de l'ordre de 105 W. Ce type de contrôle thermique impliquant un stockage thermique pendant une durée limitée est également possible lors des déplacements de l'équipage dans la cabine ou lors de l'évacuation du pas de tir (activité métabolique jusqu'à 350 W, durée inférieure à 30 minutes).

Le contrôle thermique par ventilation permet de couvrir ces différents cas. Les caractéristiques de la ventilation du scaphandre sont résumées dans le tableau 7. Le refroidissement par boucle liquide n'est pas indispensable ; il induirait un accroissement de la masse du scaphandre, une interface supplémentaire avec HERMES et augmenterait la durée de l'habillage (voir paragraphe "interfaces et procédures").

Nature du contrôle thermique → Caractéristiques du gaz de ventilation ↓	Contrôle thermique efficace Activité métabolique < 180 W Transpiration modérée Pas de stockage thermique	Contrôle thermique acceptable Activité métabolique < 180 W Transpiration importante Pas de stockage thermique	Contrôle thermique minimal Durée limitée Transpiration importante Stockage thermique
Nature	Air à 1013 hPa	Oxygène à 450 hPa	Oxygène, 450 à 1013 hPa
Température	20 à 30°C	A définir	A définir
Humidité	40 à 70 %	0 %	0 %
Débit	2,8 à 3,0 g/s	0,8 à 1,0 g/s	0,25 g/s (assure les besoins respiratoires minimaux et le désembuage de la visière).

Tableau 7 : Contrôle thermique du scaphandre

Ergonomie

Le port du scaphandre durant le lancement et la rentrée doit être compatible avec les tâches nominales de l'équipage et donc présenter des contraintes ergonomiques minimales. Cela signifie que la position assise en scaphandre doit être confortable, que les contraintes de mobilité et de dextérité ainsi que les limitations du champ visuel introduites par le scaphandre doivent être compatibles avec le pilotage d'HERMES. Le scaphandre doit présenter également un encombrement minimal afin de faciliter les opérations d'évacuation d'urgence au sol et la mobilité en orbite. De plus, les contraintes de masse de la capsule et d'HERMES imposent que le scaphandre ait une masse aussi réduite que possible. L'ensemble de ces considérations ne peut être cohérent qu'avec un scaphandre souple. Les exigences concernant les aspects ergonomiques d'un tel scaphandre dans HERMES sont détaillées ci-après.

Mobilité - Dextérité

Les limitations de mobilité sont maximales lorsque le scaphandre est pressurisé. Afin de minimiser les contraintes, le scaphandre est pressurisé à une pression de fonctionnement minimale compatible avec la protection contre l'aéroembolisme, c'est-à-dire 450 hPa. Un niveau de pression plus faible, de l'ordre de 250 hPa peut être envisagé pour une durée limitée (15 mn) pour effectuer des tâches liées à la sécurité exigeant une mobilité et une dextérité accrues.

Lorsque l'équipage est assis dans le poste de pilotage, les opérations en relation avec la sauvegarde de l'équipage ou le pilotage d'HERMES exigent que :

. La position neutre du scaphandre pressurisé soit la position assise pour éviter au spationaute un effort permanent de maintien en position.

. La mobilité permise par les articulations des bras et des épaules du scaphandre permette une enveloppe d'atteinte compatible avec l'aménagement des commandes dans le cockpit d'HERMES, ainsi qu'avec les commandes du scaphandre lui-même.

. La dextérité offerte par l'association gant-commande soit suffisante pour le contrôle d'HERMES ou du scaphandre.

Des essais du scaphandre de secours soviétique de Soyouz ont été réalisés dans une maquette d'HERMES et ont montré la validité du concept de scaphandre souple. Les contraintes introduites par les déplacements de l'équipage en scaphandre dans la cabine sont très liées aux procédures envisagées (scaphandre pressurisé ou non - voir paragraphe "interfaces et procédures"). Néanmoins, cela implique de prévoir pour l'aménagement d'HERMES une taille suffisante des passages dans HERMES ou entre les sièges, des issues et d'installer des aides à la mobilité pour faciliter l'évacuation au sol.

Visibilité

Il est impératif que l'équipage en scaphandre puisse avoir une visibilité correcte, c'est-à-dire une bonne qualité de vision au travers de la visière et un champ visuel adéquat. Le champ visuel minimal requis pour la visibilité des commandes, des connexions du scaphandre et des hublots étant de + 15° vers le haut, - 70° vers le bas et ± 90 ° sur les côtés, les mouvements de tête s'avèrent nécessaires. Ceci est réalisable soit par la possibilité de rotation du casque par rapport au scaphandre, soit par mouvement de la tête au sein d'un casque intégré au scaphandre. La position du pilote, donnée par l'ensemble siège/sangles de siège/scaphandre pressurisé ou non doit assurer une position de l'oeil adéquate.

Protection contre les accélérations et les chocs

Une protection anti-g est requise lors de la séparation d'urgence de l'avion spatial et du lanceur, l'équipage ayant un rôle actif à jouer pour le retour sur Terre. Lors de l'établissement du profil d'accélération + Gz le plus contraignant, la mise en accélération est relativement faible, de l'ordre de 0,2 Gz/s. Une valeur maximale de 5,2 Gz est attendue ; l'équipage devra supporter une accélération supérieure à 3 Gz durant 30 s dont 15 s au-dessus de 5 Gz. Afin de maintenir les performances de l'équipage dans cette phase, la protection par vessies anti-g intégrées au scaphandre et l'exécution de manoeuvres respiratoires sont envisagées.

La réduction du volume sanguin en orbite et sa redistribution vers les parties basses du corps sous l'effet de la gravité durant la rentrée entraînent des difficultés pour l'équipage à conserver la position debout et une capacité réduite à supporter les accélérations + Gz. La pressurisation des vessies anti-g durant et après la rentrée permet d'éviter l'afflux sanguin vers les jambes. Le faible niveau d'accélération lors de la rentrée (inférieur à 2 Gz) n'introduit pas de problème physiologique particulier.

La protection contre les chocs durant le lancement, la séparation, la descente et l'atterrissage de la capsule nécessitent une position correcte de l'équipage : dos, épaule et tête contre le siège. Le maintien dans cette position est obtenu par l'ensemble siège/sangles de sièges/appui-tête et accoudoirs qui doit rester compatible avec le pilotage d'HERMES. De même le harnais de siège doit être compatible avec le port du scaphandre, pressurisé ou non. La protection de la tête des spationautes dans la capsule ne requiert pas de casque dur. Le scaphandre peut donc être équipé d'un heaume souple.

Information et communications

Les fonctions d'information et de communications doivent permettre les communications entre l'équipage et le sol et entre les spationautes en scaphandre ainsi que la surveillance des paramètres de fonctionnement du scaphandre, des données biomédicales et l'émission d'alarmes. La réception d'alarmes provenant de l'ECLSS et la transmission à l'équipage doivent également être assurées. Néanmoins, le maintien de la pression totale et la fourniture d'atmosphère respirable qui assurent la survie du spationaute ne dépendent pas des fonctions d'information et de communications.

Lorsque le scaphandre est porté préventivement, la transmission d'informations à l'équipage permet d'améliorer ses performances et son confort pour l'exécution de la mission, la surveillance de la mise en oeuvre du scaphandre (connexions correctes, fermeture de la visière) et les procédures de test avant le lancement ou la rentrée.

Survie et sauvetage après le retour de la capsule

La survie de l'équipage après éjection et atterrissage ou amerrissage de la capsule doit être assurée pendant au moins 24 heures. Les fonctions suivantes doivent être assurées :

. Fourniture d'atmosphère : assurée par la capsule (ventilation par de l'air extérieur). La continuité de la fourniture respiratoire entre le scaphandre et l'ambiance de la capsule doit être assurée.

. Communications, localisation : assurées par la capsule

. Nourriture, boisson, trousse de secours : stockage dans la capsule

. Sauvetage en mer : récupération de toute la capsule ou récupération individuelle, cette dernière solution exigeant une flottabilité individuelle et un harnais de hissage individuel. La première solution serait préférable.

INTERFACES ET PROCEDURES

Les difficultés essentielles induites par l'utilisation de scaphandres pressurisés sont : leur intégration dans un poste de pilotage aux dimensions réduites, leur utilisation dans les volumes confinés d'HERMES, leur compatibilité avec des conditions d'environnement très diverses et leur insertion dans des opérations déjà compliquées par ailleurs. Sous réserve de remettre en cause la validité même du concept de scaphandre pressurisé, il est indispensable de définir des interfaces simples et des procédures d'utilisation réalistes dès la phase d'établissement des exigences.

Afin de maintenir ces problèmes d'intégration à un niveau acceptable, le choix a été fait de limiter le domaine de protection du scaphandre aux situations où il demeure le seul et ultime recours durant les phases critiques du vol atmosphérique. Dans la mesure où elles n'introduisent pas de contraintes supplémentaires sur le scaphandre et ses interfaces, des situations de sauvegarde en orbite peuvent également être couvertes moyennant des procédures d'utilisation adaptées. Le schéma du scaphandre et de ses interfaces avec HERMES proposé sur la figure 6 répond aux exigences d'un système de protection, minimum et cohérent, dimensionné pour couvrir en priorité les phases critiques du vol atmosphérique piloté, y compris une éventuelle éjection à grande vitesse et haute altitude.

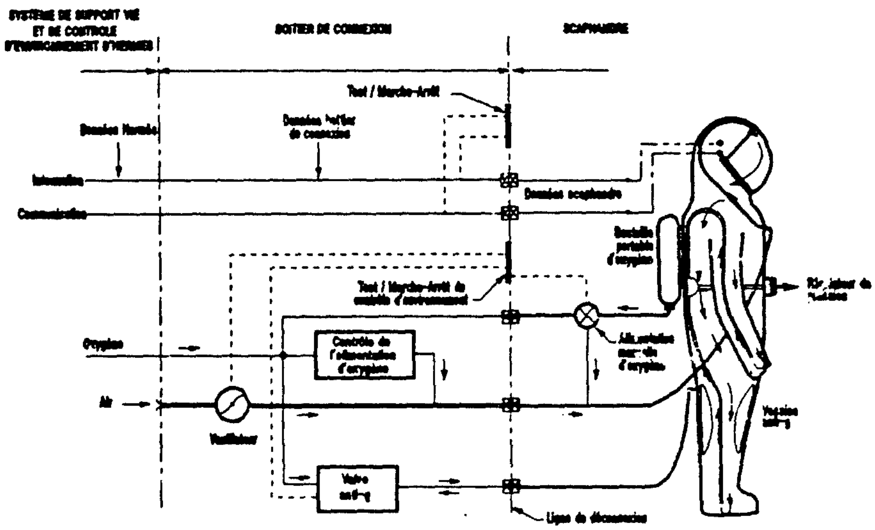


Figure 6 : Architecture du scaphandre et interfaces avec HERMES

Typique du lanceur envisagé, la rapidité de divergence d'évènements catastrophiques est telle que la séquence d'éjection pourra être initiée à l'insu de l'équipage par le segment sol, voire de façon automatique. Cela implique pour le scaphandre d'être dans une configuration telle qu'il puisse être opérationnel quasi-instantanément. Le port préventif du scaphandre est donc nécessaire au moins pendant certaines périodes de mission bien que leur déroulement soit nominal : ceci définit le mode nominal d'utilisation.

Dans le cas de phénomènes à divergence lente, ou lorsque les fonctions de protection physiologique d'HERMES ne sont plus que partiellement remplies par le véhicule, le scaphandre est utilisé pour suppléer aux fonctions défaillantes : c'est le mode de secours.

Enfin lorsque, à la suite d'une défaillance complète d'HERMES, le scaphandre doit assurer seul les fonctions de protection et de support-vie, il s'agit du mode d'ultime secours.

Mode nominal

Le port du scaphandre est incontestablement une contrainte pour l'équipage, on cherche donc à la minimiser de la façon suivante :

. Pendant les phases à divergence rapide, lancement jusqu'à insertion en orbite et rentrée atmosphérique, le port préventif du scaphandre est indispensable. HERMES maintenant une pression atmosphérique normale, le scaphandre n'est pas pressurisé, seulement ventilé avec de l'air cabine. Il est en revanche prêt à être pressurisé instantanément et automatiquement en cas de besoin. L'équipage étant normalement installé dans le poste de pilotage durant ces phases, aucun déplacement en cabine n'est prévu.

. Pendant les phases à divergence lente, phase orbitale jusqu'à l'impulsion de désorbitation, le scaphandre est enlevé pour des raisons évidentes de confort. Cela implique d'une part de le stocker dans un endroit qui restera accessible en secours et d'autre part de pouvoir l'endosser à nouveau. Etant donné que le volume central est le seul à offrir un volume suffisant pour les opérations d'habillage et déshabillage, c'est également le lieu de stockage. Les déplacements entre volume central et capsule se font avec le scaphandre ouvert et aussi rapidement que possible.

. Les fonctions assurées par le scaphandre sont destinées à en garantir le confort et donc la productivité de l'équipage assis dans le cockpit. Les interfaces avec les fonctions HERMES sont réalisées par un ombilical déconnectable :

- contrôle thermique et renouvellement de l'atmosphère interne par ventilation d'air prélevé en cabine
- information et communications autorisant le dialogue entre spationautes et avec le sol ainsi que la surveillance des paramètres spationaute-scaphandre
- alimentation des vessies anti-g pour l'aide à la réadaptation cardio-vasculaire au retour de mission
- réalisation des tests de contrôle de bon fonctionnement avant l'abord des phases critiques.

L'ergonomie du scaphandre doit permettre l'exécution normale des tâches de pilotage et des opérations nécessaires à la sécurité, d'où des impératifs de mobilité, de dextérité et de visibilité.

<u>Mode de secours ultime</u>

Ce mode entre en vigueur de façon entièrement automatique, dès lors que la pression cabine d'HERMES chute en dessous de 450 hPa. Il suppose donc par définition que le scaphandre, pressurisé à 450 hPa absolus, ait été revêtu au préalable et connecté à une source d'oxygène de pressurisation. L'analyse des évènements redoutés montre que l'on peut réduire au seul cockpit le lieu d'HERMES où ce mode est indispensable. En effet, pendant les phases atmosphériques où les risques de dépressurisation sont maximaux, l'équipage se trouve en permanence dans le cockpit, et en cas de perte de pression en orbite suite à un accident réaliste, l'équipage aura eu le temps de rejoindre le cockpit en scaphandre pendant la période de compensation (voir procédures de secours détaillées plus loin).

Les fonctions du scaphandre utilisé en mode d'ultime secours sont d'assurer la survie de l'équipage d'une part en réalisant les deux fonctions essentielles du support-vie, maintien de la pression totale et d'atmosphère respirable, et d'autre part en permettant au spationaute assis dans le cockpit d'exécuter les manoeuvres de sa propre sauvegarde : pilotage d'HERMES vers un site d'atterrissage, opération du scaphandre et initiation d'une éventuelle séquence d'éjection.

Du fait de la rigidité du scaphandre une fois pressurisé, les aspects de mobilité des membres et dextérité des gants sont les plus critiques. Ceci justifie d'une part que l'on limite au seul cockpit, où les besoins de mouvements sont réduits, la capacité d'ultime secours, et d'autre part que l'on offre la possibilité d'une pressurisation temporaire à une pression plus faible de 250 hPa.

<u>Modes de secours</u>

Ces modes interviennent lorsque le scaphandre n'a pas à assurer le maintien de la pression totale mais seulement la protection respiratoire (contamination sur le pas de tir, contamination de la cabine ou faible pression partielle d'oxygène). Ils interviennent également comme intermédiaires entre les modes nominal et ultime en cas de déviation hasardeuse du scénario nominal.

Suit une liste d'évènements redoutés et des procédures de secours associées. Ces procédures, qui consistent en général à revêtir le scaphandre dans le volume central, à se déplacer, scaphandre ouvert, vers le cockpit puis à se connecter, une fois assis, aux sources d'alimentation d'HERMES (oxygène, air, électricité, communications...) permettent de ne pas ajouter de contraintes d'interface à celles des modes nominal et ultime.

<u>Perte lente d'atmosphère en orbite</u>

Pendant la période de compensation de la pression cabine par les réserves d'HERMES, l'équipage initialement en bras de chemise revêt le scaphandre dans le volume central, puis se déplace vers le cockpit où il se met en configuration prêt pour le mode ultime. La durée d'habillage est l'élément critique qui dimensionne la fuite maximale tolérée.

<u>Contamination en orbite</u>

Grâce à l'utilisation d'un masque à oxygène offrant une protection immédiate, le scaphandre est revêtu dans le volume central. L'équipage rejoint ensuite le cockpit d'où il procède aux opérations de purge.

Evacuation au sol en ambiance contaminée

Avant le lancement ou après l'atterrissage, l'équipage en scaphandre déconnecte l'ombilical, ce qui met en service la bouteille d'oxygène portable dont l'autonomie couvre la durée de l'évacuation.

Le tableau ci-dessous rassemble les différents modes opératoires du scaphandre selon les conditions d'environnement dans HERMES et selon l'activité des spationautes : ombilical "connecté" assis dans le cockpit, ombilical "déconnecté" pour les déplacements en cabine.

MODE	CONDITIONS D'ENVIRONNEMENT	CONFIGURATION DU SCAPHANDRE	FONCTIONS REALISEES PAR LE SCAPHANDRE
Nominal	Pression supérieure à 860 hPa et atmosphère respirable	Scaphandre non connecté pour déplacement en cabine Visière ouverte	Scaphandre non pressurisé Respiration : par l'ouverture de la visière Contrôle thermique : par l'ouverture de la visière - Stockage thermique
		Scaphandre connecté dans le cockpit Visière fermée Alimentation d'air	Scaphandre non pressurisé Respiration : alimentation d'air Contrôle thermique : ventilation en air (2,8 à 3,0 g/s)
Secours	Pression supérieure à 450 hPa et/ou Atmosphère contaminée et/ou Taux d'oxygène insuffisant	Scaphandre non connecté pour déplacement en cabine et évacuation Visière fermée Alimentation d'oxygène (source portable)	Surpression de 5 à 10 hPa Respiration : fourniture d'oxygène pur Contrôle thermique : -Minimal si scaphandre non connecté (désembuage) -Acceptable si scaphandre connecté (ventilation par oxygène - 0,8 à 1,0 g/s)
		Scaphandre connecté dans le cockpit Visière fermée Alimentation d'oxygène	
Secours ultime	Pression inférieure à 450 hPa	Scaphandre connecté dans le cockpit Visière fermée Alimentation d'oxygène	Maintien de la pression totale à 450 hPa (temporairement 250 hPa pour une mobilité et une dextérité accrues) Respiration : oxygène pur Contrôle thermique : ventilation par oxygène - 0,8 à 1,0 g/s

Tableau 8 : Utilisation du scaphandre dans ses différents modes opératoires

CONCLUSION

Etant donné l'étendue du domaine de vol de l'avion spatial HERMES lancé par Ariane 5, ainsi que l'étendue du domaine d'éjection, le port préventif par l'équipage de scaphandres à pression totale est une mesure indispensable, soit pour asseoir la crédibilité d'une capsule éjectable à M = 7 - Z = 60 km, soit comme partie intégrante d'un système d'éjection plus léger offrant une protection moindre.

Les fonctions que doivent remplir les scaphandres conçus comme des équipements de survie sont avant tout des fonctions de survie : maintien de la pression totale, fourniture d'atmosphère respirable. La survie de l'équipage en scaphandre exige également que celui-ci soit capable d'exécuter les manoeuvres nécessaires à sa sauvegarde : pilotage d'HERMES jusqu'à l'atterrissage, opération du scaphandre. S'ajoutent donc des fonctions de confort, d'environnement, d'ergonomie - mobilité, dextérité, visibilité -, d'information et communications.

Enfin, le scaphandre doit être compatible d'autres fonctions telles que protection anti-g, flottabilité individuelle, harnais de sécurité pour lesquelles il constitue un support d'intégration judicieux.

Finalement, et c'est là que réside l'essentiel des difficultés, il s'agit d'intégrer le système scaphandre dans l'avion spatial aussi bien du point de vue des interfaces que du point de vue des procédures. La philosophie d'intégration retenue est la suivante : étant donné les multiples redondances d'HERMES, le scaphandre est un équipement d'ultime secours, une ultime redondance. Il est donc optimisé pour couvrir l'évènement redouté majeur qui est la perte de pressurisation du cockpit. La rapidité de divergence des évènements redoutés pendant les phases atmosphériques impose le port préventif du scaphandre et crée ainsi la nécessité d'un mode nominal avec ses besoins opérationnels inévitables. Entre ces deux modes, ultime et nominal, existe une multitude de situations dégradées que l'on propose de couvrir par des procédures, fussent-elles contraignantes, plutôt que par des équipements supplémentaires allant à l'encontre des exigences d'un système de sécurité : simplicité et fiabilité.

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SPACE CRAFT ESCAPE

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CREW ESCAPE PHILOSOPHY

Safe crew escape from spacecraft is extremely difficult to engineer and has large cost, mass and safety implications. Because of these factors, a calculated risk was apparently taken not to provide other than the most rudimentary means of crew protection for space programmes. This has been true for all programmes. Infact the apparent logic adopted is analogous to aircraft programmes in which only the prototype is fitted with ejection seats to protect the crew in the high risk phase of the early flight test programme. Production versions are designed for maximum reliability and safety short of providing for crew escape. A calculated risk is taken that on-balance it is acceptable to risk the loss of aircraft and possibly the occupants than introduce the mass, cost and complexity of a crew escape system. The manned space programme, being an extension of aviation technology, apparently adopted this well tried and logical philosophy and this proved acceptable - until the Challenger tragedy. With the exceptionally high visibility of the space programme, it is now clear that the use of this previously acceptable logic is invalid and provision must be made for crew escape.

WHAT CAN BE DONE?

a) Off-the-shelf

The initial reaction to Challenger was to see if an off-the-shelf solution to the problem was available. This reaction was noted in all space agencies, not just NASA, as the general problem of providing crew escape was reconsidered. It has taken several years for the space community to begin to come to terms with the inadequacy of off-the-shelf equipment which is designed for a totally different requirement. Some of these requirements are as follows:

i) **Limited Performance**

The 0-0 to 600 knot up to 50,000 feet ejection envelope is too small to be of real value for spacecraft crew escape.

ii) **Size Adjustable**

Seats are adjustable for a wide range of occupants, whereas the spacecraft seat occupant is clearly identified long before the mission, thus enabling the seat to be tailored to the occupant.

iii) **Field of View**

All round visibility essential for combat aircraft is not required for spacecraft, enabling a more advantageous distribution of seat subsystems for spacecraft use.

iv) **Durability and Serviceability**

An ejection seat needs to withstand abuse especially during combat operations and must be easily serviced. A spacecraft ejection seat will, it is hoped, be treated rather better enabling lighter, less durable materials to be used in its construction.

In summary, the ejection seats are designed for a very different scenario and the design compromises which are acceptable for military aircraft render them unsuitable for spacecraft use. Despite these major shortcomings, two near term programmes will still use off-the-shelf ejection seats.

b) Extraction Systems

The use of existing extraction systems to pull the crew from the spacecraft presently presupposes that time is available and the vehicle is stable enough for an orderly escape. The performance envelope of extraction systems is also very small, reducing their value for spacecraft crew escape. Over-the-side bale out falls into the same category, except that performance is further limited to low speed stable flight.

c) Tailored Conventional Ejection Seats

An alternative to the use of off-the-shelf ejection seats is the adaptation of an existing ejection seat to optimise its design for use in spacecraft. This could be achieved by the deletion of non-essential functions, such as vertical seat adjustment, in order to minimise installed mass. The ejection performance envelope can also be increased slightly by the use of improved limb restraint and some windblast protection.

In general, however, seat performance can only be increased to the present open ejection seat limits of 100,000 feet and Mach 3. The gains of such tailoring are expected to be realised by a reduction of installed mass and possibly improved packaging of subsystems to provide a better cabin interface.

d) Crew Module Escape System

Several projects have considered, or are considering, the adoption of crew modules, in which a portion of the fuselage containing the crew cabin is ejected and recovered. Such an approach offers potentially excellent improvements in the high speed, high altitude regime, but introduces difficulties in the low level, low speed case. A crew module must be separated from the parent vehicle by severing every interconnection, increasing the complexity of these connections for normal operations. A large and heavy propulsion system is required to propel the vehicle, which must then be stabilized and finally recovered under large parachutes. Impact attenuation and flotation must be catered for to protect the crew on landing. Although such a system offers many advantages, it represents a highly complex and heavy solution which has a significant impact on the vehicle payload.

e) Individual Crew Ejection Seats

Hermes programme management are fully addressing the subject of safety and are investigating all of the options for crew escape. To this end, they have issued study contracts fo. various of the above options and have noted the factors mentioned. To complete their studies, Martin-Baker was issued with a feasibility study contract in February 1989 which will be completed in early May. The general design requirement is for individual ejection seats capable of providing safe escape from the launch pad to an altitude of 60 km, speed of Mach 6.5 and maximum dynamic pressure equivalent to 600 knots at sea level. During the landing phase, recovery is required from 60 km down to landing. Escape on the launch pad must result in the crew descending on fully open parachutes at least one kilometre from the launch tower.

Hermes has a crew of three, two pilots seated side-by-side and a crewmember, seated directly behind the pilots. The spaceplane is mounted on top of an Arian 5 booster for launching into space. Re-entry is as a glider with control being provided conventionally by the two pilots.

Throughout the study, the prime requirement for minimum mass has been paramount, together with the safe operation of the escape system.

Our initial studies have quickly identified the need for encapsulation to protect the ejectee from kinetic heating during high speed escape rather than for windblast protection, although this too is a factor.

We have endeavoured to minimise the escape system design impact on Hermes by simplifying the installation, retaining pilot field of view and ejecting the crew through the smallest apperture. We believe that our proposed preliminary design meets most of these objectives.

From the various trade studies which have been made during the feasibility study, we have selected the following system which currently appears to offer the optimum solution.

PRELIMINARY DESIGN DESCRIPTION

General Description

It is proposed that each crewmember be provided with an encapsulated ejection seat which also provides the function of crew seat for normal operations (figure 1).

Structural Interface

The ejection seat would be mounted on guide tubes which extend from the cabin floor to roof. The upper ends of the guide tubes attach to cross tubes extending across the upper part of the cabin.

These guidetubes would also act as ejection guns as they incorporate inner piston tubes, the upper ends of which engage in a latch at the top of the ejection seat. On ejection, the guidetube/ejection guns pressurize causing the inner piston tubes to rise propelling the seat up the outer guidetubes which would remain in the cabin.

Location and Adjustment of Crewmember

The crewmember would be seated on specially moulded inserts which correctly position him/her in the cabin. No vertical adjustment is provided. With so few astronauts, for which the anthropometric data is well known, we see no advantage in providing heavier electro/mechanical seat adjustment.

Because the pilots may need to lean forward to adjust the controls, shoulder harness retraction is proposed. This will enable forward movement with acceleration locking and with ballistic retraction prior to ejection.

The tilt facility to raise the crew's heads to withstand acceleration during launch can be provided by manually tilting the sitting platform within the capsule and not by tilting the seat as a whole. This is expected to provide the required positioning for the lightest mass. On ejection, a simple ballistic actuator would retract the occupant sitting platform to the correct position.

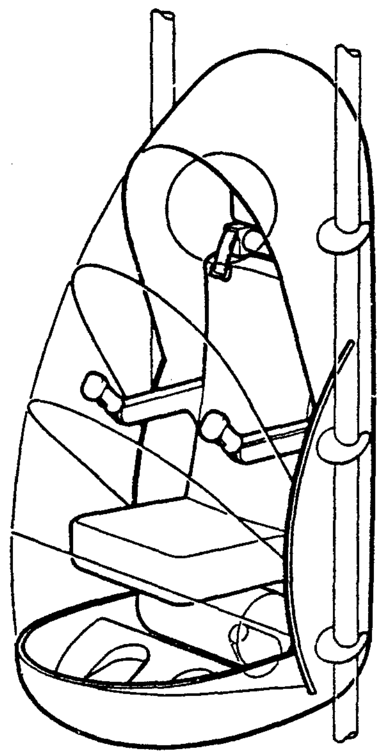


FIGURE 1

Escape Parameter Definition

During the feasibility study, we have considered only the specified operating envelope, i.e. zero-zero to 60 km at Mach 6.5. Extension of this envelope will be considered when the basic design has been fully established. At the present time limits are expected to be set by the capability of the retardation/stablization, thermal protection and life support systems.

Human Engineering

The ejection seat is being designed to include the full range of percentiles wearing the light pressurized Intra Vehicular Activity (IVA) suit. The detailed study will form part of the second phase of the feasibility study.

Normal Operating Requirements

The design would take full consideration of the normal operating requirements. During the preliminary study, it became apparent that ingress and egress to the pilot seats would require very careful design consideration, as the cabin is positioned "on-end" in the launch attitude. It will be of special importance to provide rapid egress in the emergency case. We are reviewing several options including dropping one pilot seat back on shock struts, the crewmember seat being installed to one side for this purpose. Alternatively, all seats could swing down towards the "upright" position.

Emergency Escape Initiation

Ejection initiation presents a major design difficulty, as this function cannot be left to the crew as in military aircraft. In many scenarios the crew will receive little definite information to indicate the possible need to eject. The time taken for a problem to become a catastrophe may well be too short and present insufficient severity indications to enable the crew to react and make a decision to initiate ejection before an explosion occurs. We have therefore studied the three prime escape initiation methods as follows:

a) **Automatic Ejection**

A signal would be required to be sent by the spacecraft system (computer) to initiate crew ejection on the launch pad. The parameters under which ejection would be initiated must be determined by the prime Contractor, as will the method of generating and transmitting the signal. In order to respond to the ejection signal, the seat sequencers will need to be active requiring a power supply from the spacecraft, via a battery, to ensure power supply continuity in the event of a spacecraft power failure. The use of one master ejection sequencer with slaved sequencers on the two remaining seats is being considered in order to reduce costs and to provide a central control for ejection sequencing.

b) **Ground Control Initiated**

The requirement to initiate a Command Ejection by Ground Control is also considered likely, especially if the crew is incapacitated, and could presumably utilize the same signalling circuits as the automatic system.

c) **Crew Initiated**

Individual ejection initation is considered most likely to be required by the two pilots. It was felt that pilot initiated ejection would be most likely to occur during the final phase of recovery when problems were encountered on the landing approach. Seat firing handles would need to be designed with maximum safety in mind and must not be prone to snagging.

The ejection controls could be incorporated in the arm rests and serve the dual purpose of hand grips which the ejectee can hold to restrain the arms.

MODE OF OPERATION

Initiation phases

Launch Phase

Initiation would be automatic via the main computer control. Alternative ground control can remotely initate ejection. The pilots would have an ability to initate a sequenced ejection at all times if the system was armed.

Dormant Phase

The escape system would be automatically de-activated above the ejection operational limit to prevent accidental initiation during the mission.

Re-entry

At a point to be determined, the system would be automatically armed to enable ejection initiation. Ejection is most likely to be initiated by either pilot during re-entry, with automatic or ground control initiation less likely.

The rear crewmember should be positioned for ejection at all times that the system is armed.

Pre-ejection Action

In the launch phase, the crewmembers are passengers and could therefore sit with arms and legs in the ejection position and could have the clamshell closed to save time. In the re-entry phase, the pilots will need to have full access to the controls and instruments and therefore must have the clamshell open. Because of the re-entry phase requirements, it would be necessary to have a clamshell closure device and therefore little or no advantage is seen in having the clamshell closed for launch, as in any case it is likely that this would be unacceptable to the crew.

In order to save weight, it is proposed to dispense with restraint systems and require that the pilots place their feet on foot rests within the capsule and grasp the arm rest/ejection controls before seat initiation. For the launch phase where remote initiation would probably occur, it will be essential that the crew be in the eject position.

A shoulder harness retraction unit will be provided as the pilots would be expected to need to lean forward to reach controls. Ballistic retraction of the pilots shoulders will take place as a pre-ejection function. The crewmember may not be provided with a retraction device because he could be pre-positioned for escape.

Ejectee Protection

The ejectee would be required to bring his/her feet back inside the capsule and place them into special foot rests which secure the feet in place and provide a signal that the feet are positioned within the capsule. The hands would be located on the armrests and handgrips, again providing a positive signal of correct, safe, crew positioning. On seat initiation the feet would be locked in place by sole latches (like ski attachments) and the harness would tension.

Various forms of protective shield have been considered but, so far, the best appears to be a laterally pivoted clamshell, the segments of which slide up under each other for compact stowage above the headrest. On ejection these clamshell shutters are ballistically closed to protect the ejectee. It is not intended that the capsule be pressurized as the IVA suit offers this protection and the clamshell would be provided to protect against transient windblast and heating during the initial exposure of the seat. Immediately after rocket burn-out, the seat may be rotated to face its back into the wind so that most of the windblast and kinetic heating will be taken by the smooth rear of the seat. In this position the clamshell would serve to "streamline" the seat to reduce heat stagnation at high velocities.

Following the receipt of information from the Royal Air Force Institute of Aviation medicine, it appears feasible from a physiological view point to keep the seat "face into the wind". The resulting eye-balls out deceleration of 10g for 20-30 seconds is physically tolerable and the use of a head support (inflatable) would minimise head nod. Dispensing with the post rocket burn rotation would certainly simplify seat ejection and control and will be studied further.

Inner thermal protection will also be provided to minimise the transmission of high (or low) temperatures to the ejectee.

At seat/man separation after ejection, the clamshell separates prior to parachute inflation. This can be arranged to coincide with increased deceleration from the developing parachute so that the clamshell peels away and down ensuring no risk of clamshell/man collision.

Ejection Path Clearance

Various hatch configurations are being studied including individual, double for both pilots plus single for the crewmember and one large single hatch. Martin-Baker prefer the single hatch concept if this can be integrated with the Hermes structure. Hatch removal could be by pyrotechnic actuators, (thrusters) or rockets. These alternatives will be studied, but is not seen as a major risk area for ejection.

Ejection Gun Operation

A simple twin ejection gun is envisaged to propel the encapsulated seat and occupant from the cabin (see structural interface).

Ejection Seat Rocket

A single nozzle rocket motor is presently proposed which would provide a two second burn and produce an acceleration of 15 g for the light subject. The fuel weight for such a motor is expected to be 35 kgs and would be capable of propelling the seat on a 1 km long horizontal trajectory.

Trajectory

Ejection from the vehicle launch position should result in the crewmember reaching the ground as far from the vehicle as possible in the shortest time.

In order to reduce the parachute exposure to blast and heat, it is to be proposed that the seat trajectory be as flat as possible with parachute opening delayed as long as possible (see figure 2).

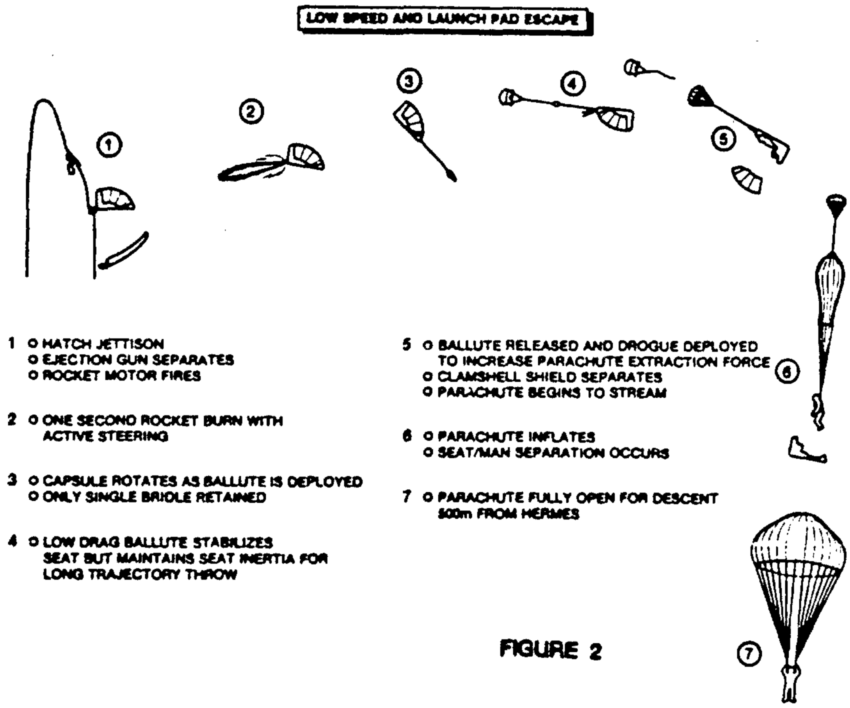


FIGURE 2

Trajectory Control

Trajectory control will be by gyro controlled nozzle vectoring as used in missile applications. Information on suitable nozzle steering systems has been obtained and is being studied for integration into the escape system.

Stability

Low Level

Any stabilizing surfaces must be of low drag in order to retain momentum for the maximum trajectory throw. A low drag ballute would offer the necessary stability with minimum drag during the majority of the seat trajectory. It is then proposed to release the ballute and deploy a high drag ribbon drogue to extract the personnel parachute.

Mid/High Level and Speed

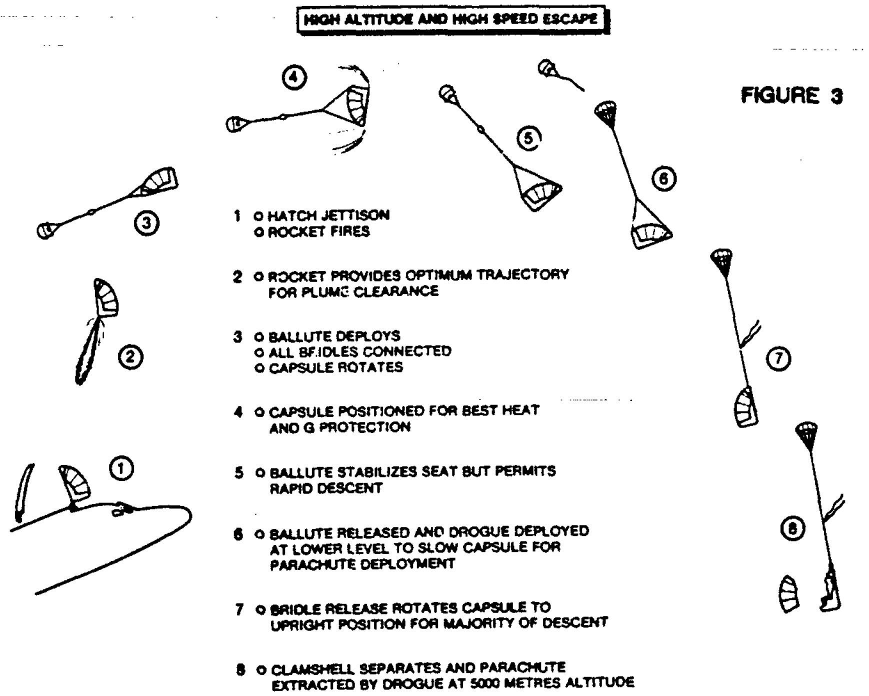
The use of a low drag ballute type drogue will be investigated to determine the best method of providing stability and deceleration at high speed and altitude. Aerofoils are expected to be unsuitable at high mach numbers due to kinetic heating which is expected to burn away any protuberances from the seat outer envelope. Ballute technology is well understood and appears capable of extension to Mach 6-7, assuming that the high stagnation temperatures of 1350°C can be tolerated. Similar Ballute studies are being conducted to stabilize the Hermes Crew Module and therefore data could be read across.

Parachute Deployment

Alternative methods of parachute deployment are being considered. The use of the drogue to deploy the parachute will minimise weight and should be satisfactory in the launch pad case in view of the high velocities generated by the propulsion system. There will never be a "zero-zero" ejection situation as parachute streaming will always take place in a high relative wind due to the high performance of the seat rocket.

At high altitudes, parachute deployment will be delayed until 5,000 metres altitude (see figure 3).

The fall back method will be parachute extraction by rocket as on Martin-Baker's United States Navy Aircrew Common Ejection Seat (NACES).



Seat/Man Separation

Martin-Baker believe that it is preferable that the ejectee separate from the seat at parachute opening. The reasons for this preferance are:

a) A smaller lighter parachute could be used as it would not be required to suspend the encapsulted seat weight.

b) No impact attenuation devices would be required.

c) The ejectue would automatically separate and not have to separate manually.

d) Ambient air breathing could be used via an anti-suffocation valve, reducing the amount of oxygen to be carried.

e) Adequate thermal protection could probably be provided by the reflective suit.

SUMMARY

The above describes the currently preferred option from among the designs so far studied. We shall, however, continue to study alternatives for seat design to identify systems which offer the best possible approach with minimum design risk.

Martin-Baker will continue to study the overall design and also initiate more detailed studies of the main elements, such as drogue stabilization, temperature extremes protection and rocket motor thrust vectoring. We shall also initiate the study of programme management and the testing and qualification of such a system.

It is already apparent that the test programme would, at some point, require testing of the seat under actual conditions, if the required level of confidence is to be achieved.

The Hermes Management Team are meeting the crew safety challenge by initiating and funding wide ranging feasibility studies. They are placing equal emphasis on the Crew Escape Module concept and this study is also most promising. Hermes has the enormous advantage of hindsight which, we all know is perfect, and this valuable experience is being put to good use. We believe that this pioneering work, whether by CEM or encapsulated ejection seats (or a combination?), can provide an effective and efficient means of safe crew escape. Such a valuable prize will however not be obtained without continuing to commit the necessary resources and dedication.

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14. Abstract

This Conference Proceedings includes the Keynote Address and 12 papers from the Symposium sponsored by the AGARD Aerospace Medical Panel held in Munich, Germany from 24—28 April 1989.

With reduction of escape fatalities or injuries and improvement of out-of-the envelope ejection safety as primary goals, this Symposium addressed the latest technological advances in all areas which affect overall escape system performance and capabilities. Escapes from hypersonic vehicles and spacecraft were also considered. Portions contents
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